THE
WORLD MAGNETIC SURVEY*

BY

J. P. HEPPNER

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NASA ——— GODDARD SPACE FLIGHT CENTER ———
GREENBELT, MD.

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ABSTRACT

The mathematical and graphical description of the earth's main field has been, and is, a 'data limited' problem. The World Magnetic Survey (WMS) is an endeavor to minimize this limitation by rapidly and comprehensively blanketing the earth with magnetic field measurements. Satellite surveys, which will play a key role in the WMS, are the principal topic of this paper. Existing magnetic field descriptions, the expected results from new surveys, and the methods of obtaining these results with the POGO satellite are emphasized. It is anticipated on the basis of extrapolation from Vanguard 3 results and other considerations that a factor of 10 improvement will be obtained. This means that the average errors of 1 to 3 percent now present in field charts and spherical harmonic descriptions should be reduced to 0.1 to 0.3 percent as a result of the survey.

1. Introduction

"The World Magnetic Survey" (the WMS) denotes an international effort to obtain data for mathematical descriptions of the earth's magnetic field and its secular variations and for constructing charts of the field at the earth's surface. It is distinguished from previous survey efforts in the scope of the effort which hopefully will lead to a truly world wide coverage. In obtaining this coverage it is particularly important that: (a) emphasis be placed on the magnetically unmapped and poorly mapped regions of the globe, and (b) the survey be conducted within a time interval that is sufficiently short to not require major corrections for secular variations in describing the field at a particular date. The advantages of conducting the survey during years of minimum solar activity relate the WMS to the International Year of the Quiet Sun (the IQSY). The context of the WMS is logically extended to include studies of temporal magnetic variations at least to the degree that these variations influence the survey measurements. The future determination and study of secular variations is obviously closely related to the primary objectives of the WMS.

The principal objective of the WMS, as first proposed at the IUGG meeting in Toronto in 1957, was to obtain more accurate magnetic charts through expansion of existing surveys and creation of new programs for magnetic surveys by sea and air. The advantages of conducting surveys during years of sunspot minimum and the potential use of rockets and satellites in mapping the field were noted at the meeting of the ICSU Special Committee for the IGY (CSAGI) in Moscow in 1958 (Chapman 1960). Resolutions, recommendations, and discussions at these and subsequent international meetings (e.g., IUGG, Helsinki 1960; COSPAR, Florence 1961) gave the WMS an international foundation and established guidelines to promote compatibility of measurements from various sources. These have been described in detail in the IAGA-IUGG, Instruction Manual on the World Magnetic Survey, prepared by Vestine (1961).

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Since the proposal in Toronto in 1957 the advent of the satellite as a new vehicle for magnetic surveys has been paralleled by new reasons for needing a world magnetic survey. The need in 1957 came primarily from lack of adequate data for studying the origin of the magnetic field and its secular changes, and preparing more accurate magnetic charts for nautical and aeronautical navigation. These reasons are still fundamental but of equal importance now is the need for better descriptions of the earth's magnetic field in space. In space science, this need comes from the requirements for: (a) an accurate main field reference for satellite magnetic field experiments designed to determine the distribution of sources of magnetic disturbance, (b) describing the motions and distribution of trapped particles and the trajectories of solar particles and cosmic rays as they approach the earth, (c) determining the trapping lifetime for particles naturally or artifically injected into the magnetosphere, and (d) determining the detailed geometry of field lines for field dependent radio transmissions, for locating conjugate points, etc. In space technology, this need arises from the use of the magnetic field in spacecraft orientation control and aspect systems.

A magnetic "chart" or "map," a two dimensional representation of the field, would be of very limited use in space problems. A mathematical description on the other hand is directly useful. Thus, though one speaks of "mapping" the field, it should be understood that the objective is first a three dimensional (latitude, longitude, altitude) mathematical description of the field, and second, a four dimensional description in which secular changes are adequately known to write the coefficients as a function of time. A related question, discussed later, is whether or not world magnetic charts at the earth's surface drawn from mathematical descriptions will be more or less representative than charts constructed by contouring measurements as done in the past.

A world magnetic survey, in a strict sense, has never been made and has never been feasible by land, sea, and air if one accepts a

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definition that such a survey ideally requires global coverage on a time scale short compared to the time in which secular variations invalidate the first measurements relative to the last. This does not mean that land, sea, and air methods have become obsolete as this would be misleading in view of the complementary nature of surface and space measurements and the advantages of surface data in mapping crustal anomalies. It does however imply that satellites have made a truly world magnetic survey feasible and, if successful, it may in the future be fitting to refer to this survey as "The First World Magnetic Survey." Logically this survey will be followed by others to update the descriptions of the magnetic field and delineate the patterns of secular change.

Appropriate to this journal, satellite magnetic surveys are the principal topic of this review. Land, sea, and air surveys are briefly discussed to give perspective on the surface data available for main field analyses and to illustrate the complementary features of the various surveys. Existing magnetic field analyses are discussed. Attention is then directed to: problems in satellite surveys, details of the magnetic survey to be conducted with the POGO satellite, analysis problems likely to be encountered in arriving at the best description of the earth's field and secular variations from the data obtained, some of the preflight thoughts on methods of handling and analyzing data from POGO, and the many possibilities for studies of temporal magnetic variations using simultaneous data from the survey vehicle and surface observatories. The satellite discussion will center on the POGO (Polar Orbiting Geophysical Observatory) survey largely because details on other satellite surveys are not available. The POGO survey should, however, be adequately illustrative.

No attempt is made to provide a comprehensive list of references. Recent papers are referenced in preference to many outstanding, older publications on geomagnetism on grounds that these can be found by examination of the references in recent publications and Chapman and Bartels' "Geomagnetism" (1940).

2. Land, Sea, and Air Surveys

2.A. Observatories and Repeat Stations

Measurements on land come primarily from two sources: magnetic observatories and repeat stations. The quantity and distribution of data for the period 1905-1945 is illustrated in the Carnegie Institute's Publication 578 (Vestine, et al., 1947b). As of 1945 there were approximately 100 observatories and 2000 repeat stations where a repeat station is defined as a location occupied more than once. Since 1945 the number of observatories has increased to about 150. A recent listing is available in the Annals of the IGY, Vol. VIII, 1959. The number of new repeat stations is not readily estimated accurately but it appears unlikely that the number has greatly increased. The distribution of observatories and repeat stations is extremely spotty not only as a consequence of the distribution of land masses but also because the locations within land areas tend to be grouped. The fact that the field at a single observatory or station may not be representative of a region, because of a local anomaly, does not permit one to assign large weighting factors to observatory data relative to other observations for mapping purposes. Although these are serious disadvantages, observatories provide the most reliable data for studies of secular change and in the past the only data for studying secular change on a year to year basis. Observatories also provide the data for editing and correcting survey measurements for temporal variations when these corrections are applied.

2.B. Ship Surveys

The earliest magnetic charts, epoch 1700, were those of declination drawn from ship records of compass direction. Although magnetic measurements were made on various ocean expeditions in the 1800's (Fleming, 1939) it was not until 1905 that a serious attempt was

made to map the oceans. The most comprehensive surveys by ship were those made by the Carnegie, a non-magnetic ship constructed as a part of the Carnegie Institution of Washington's program for magnetic mapping conducted from 1905 to 1929 when the ship was destroyed by fire. The extensive coverage achieved by the Carnegie Institution's 25 year survey has been illustrated by Fleming (1939) and Vestine (1960). Ship surveys were reactivated in 1956 by the USSR non-magnetic ship, the Zarya, which in 1957 and 1958 covered 47,000 nautical miles in the Atlantic and Indian Oceans (Ivanov, 1960, 1961), and has since surveyed also in the Pacific. Using towed magnetometers measuring the scalar field, ship surveys have also been conducted on a regional scale by various groups engaged in oceanographic and submarine geologic studies and magnetic traverses have been made on various expeditions.

The relative merits of ship and aerial surveys are often compared. Such comparisons are often confused by lack of distinction between what has been achieved and what it is possible to achieve. It is obvious that ship surveys take considerably more time and global secular changes can only be studied in terms of a number of decades. There has, however, been a general belief that this disadvantage is partially counterbalanced by greater system accuracy in ship surveys because they are less susceptible to navigational errors. This belief may be justified in given cases but generalizations are not obviously justified.

2.C. Aerial Surveys

Magnetometers carried or towed by aircraft and measuring the scalar field have been used for local and regional geologic studies by commercial firms and national geological surveys for about 15 years. The data from these efforts have in some cases been available for constructing magnetic charts. About 10 years ago groups in the United States and Canada redesigned the airborne systems to provide vector measurements and later undertook magnetic surveys on a scale which

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would contribute more significantly to world magnetic charts. The Canadian Dominion Observatory survey subsequently covered Canada in a nearly uniform pattern and provided several traverses across the Pacific and North Atlantic (Serson, 1960). The U.S. Naval Hydrographic Office in 1959 initiated its plan for world-wide coverage of ocean areas under the name, Project Magnet. The coverage achieved by Project Magnet through February 15, 1963 is illustrated by the heavy lines in Figure 1. The lighter lines indicate future survey tracks. The shaded area in the Atlantic Ocean was surveyed between 1953 and 1959.

An excellent review of airborne magnetic surveys for world charts, expressing both the capabilities and the limitations, has been written by Serson (1960). A summary is hardly possible here but it will be instructive to note some of the problems encountered in aircraft surveys for later reference in discussing similar satellite problems. Serson (1960) has listed the sources of error in a vector aerial system as follows: (a) errors in measuring the magnetic field at the magnetometer with respect to the direction reference system, (b) errors in the direction reference system, (c) errors due to changes in the magnetic field of the aircraft, (d) errors due to transient changes in the magnetic field, and (e) errors in geographical position. Serson describes the approximate equivalence of the U.S. and Canadian systems. For Project Magnet, Byrnes (1960) gives the following probable errors of observations under good survey conditions: total field magnitude, ±15 gammas; angle accuracies equivalent to inclination and declination, ±0.1 degrees; geographical position, ±5 kilometers. Transformed to component errors the angle errors give north-south and east-west errors varying from zero at the equator to 100 gammas at high latitudes and vertical errors ranging from 50 gammas at the equator to zero at the dip poles. Regarding the geographical position, or navigational, errors Serson (1960) states that errors of the order of 100 to 150 gammas resulting from moderate errors of a few kilometers in navigation are responsible for the largest source of error in the results as
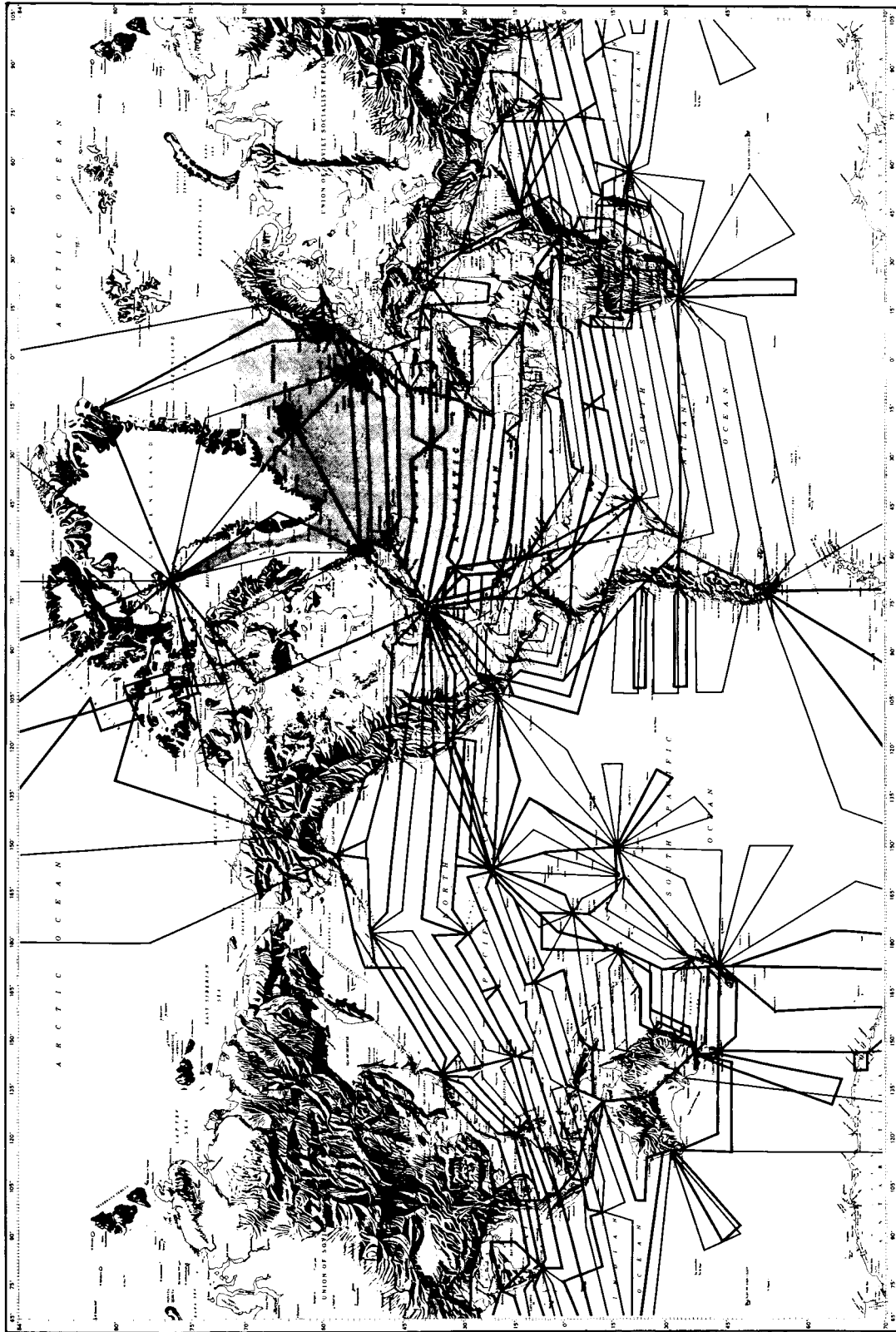
Figure 1–Project Magnet airborne geomagnetic survey tracks: 1959 to February 15, 1963 (heavy lines); future tracks (light lines); surveys between 1953 and 1959 (Atlantic Ocean shaded area). (Courtesy of U. S. Naval Oceanographic Office).

plotted on charts. It should be noted, however, that errors of 100 to 150 gammas should not result from position inaccuracies of a few kilometers in the horizontal plane in the absence of crustal anomalies. Thus in a spherical harmonic analysis limited to describing very deep sources the effective field error due to position errors is reduced to values proportional to the regional gradient if the position errors are systematic. If the position errors are random their principal effect is that of increasing the magnitude of the residuals, or noise level, already present in the analysis as a consequence of local anomalies. Returning now to field measurement errors of 50 to 100 gammas these become slightly more important than a few kilometers error in horizontal location for global harmonic analyses. The considerations of systematic vs. random errors apply equally well for these errors. Thus, for mathematical descriptions of the field, world charts, and especially studies of secular variations it is desirable to reduce the errors in aerial surveys but it is even more important that attention be directed toward avoiding systematic errors.

Another topic worthy of discussion, but not detailed here, is the relative merits of total field vs. vector measurements in aircraft surveys. Noting that the errors quoted above are probable values under good survey conditions, the total range of operational errors can be expected to be considerably larger and one can question whether the angle measurements are always of value. The answer at present and at least until methods of analysis of world wide scalar values are thoroughly demonstrated is unquestionably yes. It follows however that there may be considerable merit in flying absolute scalar magnetometers in the same aircraft with the saturable core magnetometers for checking and reducing errors.

3. Existing Magnetic Field Descriptions

3.A. Spherical Harmonic Analysis of Surface Data

The reader is referred to Chapman and Bartels (1940) for detailed discussion of the applicability of spherical harmonics to field analyses. The basic formulation is given here for later reference. In a source free spherical shell $(a < r < R)$ the magnetic potential, V, satisfies Laplaces equation $\nabla^2 V = 0$ and can be expressed in terms of spherical coordinates as follows:

$$V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} P_n^m (\cos \theta) \left[\left\{ c_n^m \left(\frac{r}{a}\right)^n + (1-c_n^m)\left(\frac{a}{r}\right)^{n+1} \right\} \right.$$

$$(1)$$

$$\left. A_n^m \cos m\phi + \left\{ s_n^m \left(\frac{r}{a}\right)^n + (1-s_n^m)\left(\frac{a}{r}\right)^{n+1} \right\} B_n^m \sin m\phi \right]$$

where c_n^m and s_n^m are numbers between 0 and 1 representing the fractional contribution from sources external to R at $r = a$. The $P_n^m (\cos \theta)$ are the partly normalized associated Legendre functions which have been extensively used in geomagnetism since their introduction by Schmidt (see Chapman and Bartels, 1940). As the magnetic force rather than the potential is the measured quantity, harmonic expressions for $F = -\text{grad } V$ are used in analysis, where F is the total vector field intensity.

Until very recently all analyses were based on the coefficients of one or more of the components

$$Z = \frac{\partial V}{\partial r} \quad \text{(vertical)} \qquad (2)$$

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$$X = \frac{\partial V}{r \, \partial \theta} \quad \text{(north)} \tag{3}$$

$$Y = \frac{-\partial V}{r \sin \theta \, \partial \phi} \quad \text{(east)} \tag{4}$$

and used only surface measurements. Thus, at $r = a$, where "a" is the earth radius, some condensation of the harmonic expressions comes from $r/a = 1$ and X, Y, and Z can be expressed as follows:

$$Z_{r=a} = \sum \sum (\alpha_n^m \cos m\phi + \beta_n^m \sin m\phi) \, P_n^m (\cos \theta) \tag{5}$$

$$X_{r=a} = \sum \sum (A_n^m \cos m\phi + B_n^m \sin m\phi) \, \frac{dP_n^m (\cos \theta)}{d\theta} \tag{6}$$

$$Y_{r=a} = \frac{1}{\sin \theta} \sum \sum (m \, A_n^m \sin m\phi - m \, B_n^m \cos m\phi) \, P_n^m (\cos \theta) \tag{7}$$

where

$$\alpha_n^m = \left[n \, c_n^m - (n+1) \, (1 - c_n^m) \right] A_n^m \tag{8}$$

$$\beta_n^m = \left[n \, s_n^m - (n+1) \, (1 - s_n^m) \right] B_n^m. \tag{9}$$

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Most of the approaches for obtaining the coefficients have differed only in numerical technique and weighting factors although there are exceptions noted later. The method used by Vestine, et al. (1947a) is illustrative. In this analysis the functions $X_n^m = dP_n^m (\cos \theta)/$ n dθ and $Y_n^m = m\, P_n^m (\cos \theta)/n \sin \theta$ tabulated by Schmidt (1935) were used for convenience. World magnetic charts compiled separately for X, Y, and Z were used to obtain from X and Y two determinations of A_n^m and B_n^m and from Z the α_n^m and β_n^m coefficients. Data were taken at intervals of 10 degrees in colatitude and longitude. Fourier coefficients a_m, b_m were first determined for $m \leq 6$ along each 10° parallel of colatitude and then fitted by the functions X_n^m and Y_n^m to obtain two values for A_n^m and B_n^m (except for zonal harmonics, m = 0, given only by X). The Fourier coefficients a_m, b_m were weighted as a function of latitude from 10 for θ = 80°, 90°, and 100° to 1 for θ = 10° and 170°. To separate internal and external sources the α_n^m, β_n^m from Z and averages for A_n^m, B_n^m from X and Y were used in Eqs. (8) and (9) to give c_n^m and s_n^m.

The above illustrates a number of features which have individually been common to a number of analyses, such as: the use of world magnetic charts for input data, the dependence on Z in separating internal and external sources, the weighting of data as a function of latitude, and the assumption that r = constant. For exceptions to several of these feature and detailed differences between analyses the reader should examine the analyses reviewed by Chapman and Bartels (1940) and the more recent analyses of Finch and Leaton (1957), Fanselau and Kautzleben (1958), and Jensen and Whitaker (1960).

In using readings scaled from the world magnetic charts the accuracy of the analysis is necessarily limited to the accuracy of the chart. This, in turn, is a function of the latitude-longitude distribution of observations, the year of the observations relative to the chart year, the measurement errors including temporal variations, and the subjective nature of contouring by hand. The latter point is not at all negligible as illustrated by comparing magnetic charts drawn by different

organizations using essentially the same data. Thus, in the past it has been argued that a better description might be obtained using only observatory values. This represents an extreme view which ignores the influence of local anomalies at observatory sites and the fact that the mutual dependence of the coefficients is such that large errors are likely to occur in regions lacking an observatory. Figure 2, by comparison with Figure 3, illustrates the detail that appears on a world chart, after corrections and analysis, relative to the detail given by an m = n = 6, 48 coefficient, representation of the field. When expanded to greater dimensions and broken into smaller contour intervals the detail in Figure 2 increases (see section maps of Vestine, et al., 1947b) whereas the detail in Figure 3 remains constant. If the small wiggles and bumps in the contours of Figure 2 are the consequence of local anomalies not being perfectly removed from the observations (which is very likely: see discussion in Section 3.C.; also note the prevalence of irregularities in poorly mapped regions) they will create errors in any spherical harmonic analysis based on chart scalings at regular grid intervals. The use of regular grid intervals is also subject to criticism on grounds that poorly mapped and unmapped regions receive the same weight as regions that are well mapped. The availability of high speed digital computers is currently providing a compromise between the various extremes. An analysis program which utilizes directly all the data that is normally used in chart making can eliminate the subjectivity of the hand contouring without being influenced by local anomalies and data distribution to any greater degree than in the contouring process. Initial steps for achieving this compromise have been made in the methods of Jensen and Cain (1962) and Fougere (1963).

Efforts to determine c_n^m and s_n^m of Eqs. (8) and (9) have placed an upper limit of several percent on the fraction of the surface field caused by external sources. Various errors may contribute to give this large upper limit but it is most probable that the accuracy is primarily limited by average errors of 1 to 3 percent in the charts used for input data. Another factor is that charts for Z are in general likely to be the
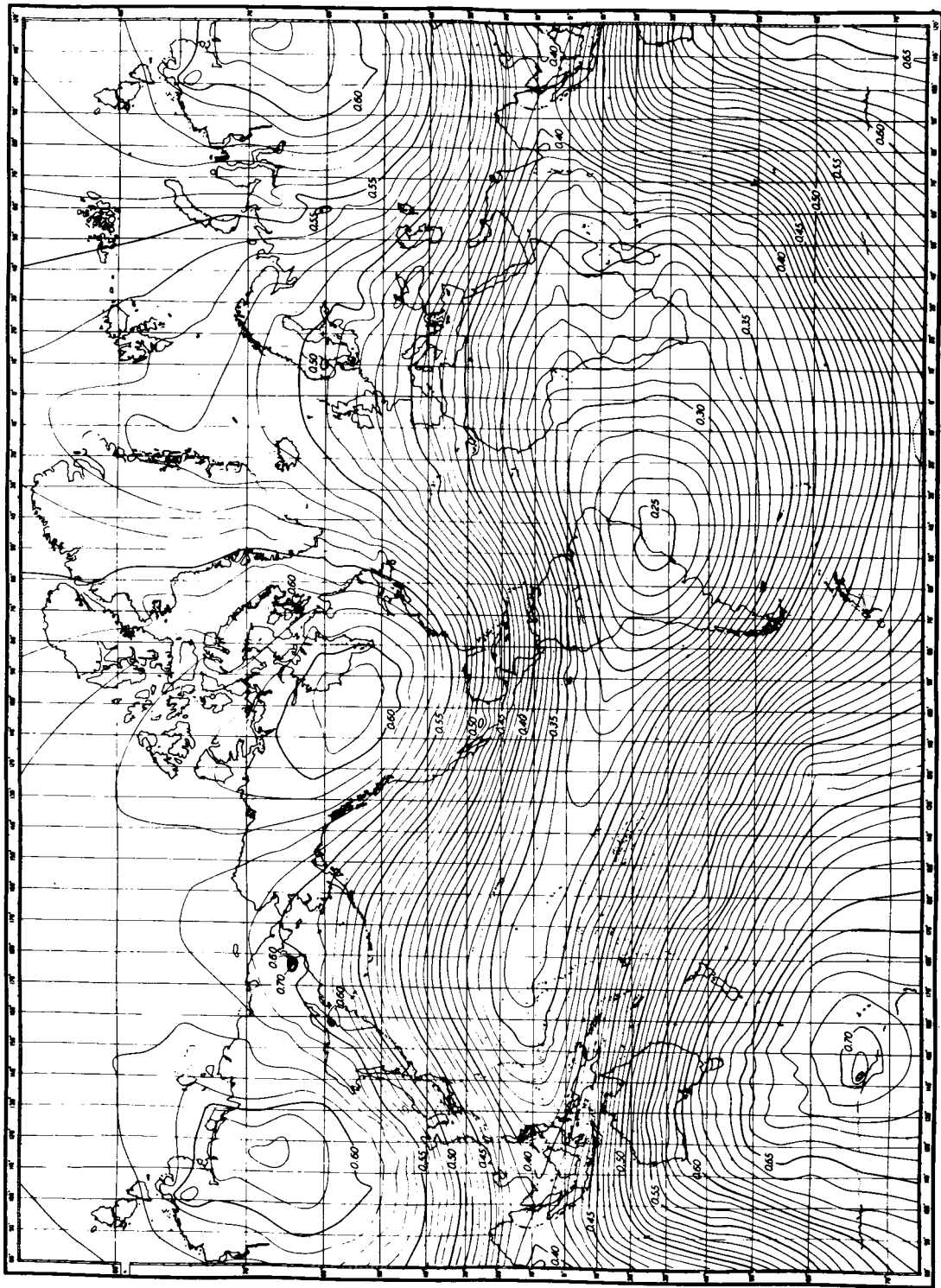
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Figure 2–Chart of total magnetic field intensity for Epoch 1945 in units of Gauss (Vestine, et.al., 1947b).
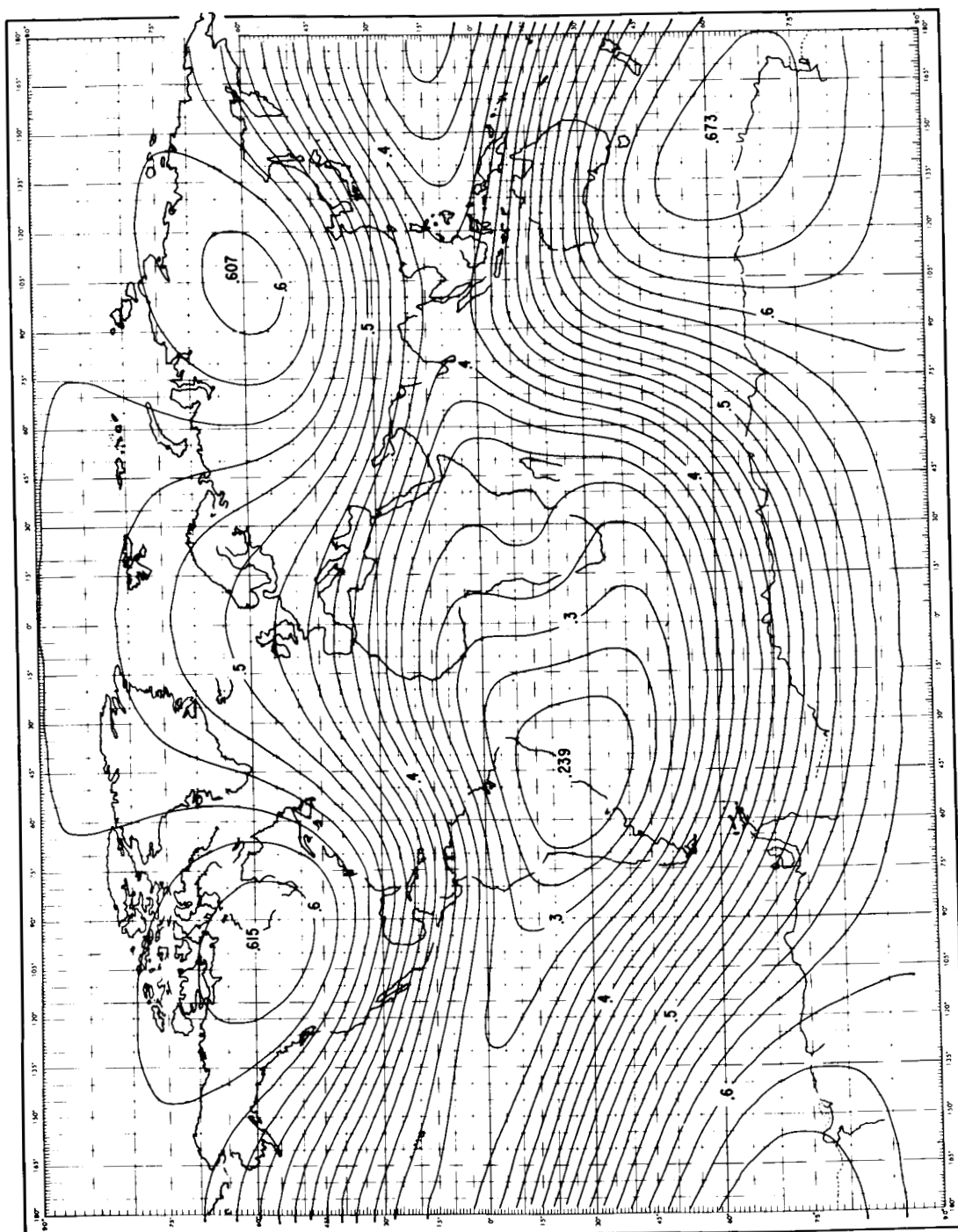
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Figure 3—Machine plot (Cain and Neilon, 1963) of total magnetic field intensity for 1960 given by 48 coefficient expansion of Jensen and Cain (1962)

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least accurate of the three components. The sensitivity to the accuracy of the Z charts is illustrated by an example in Chapman and Bartels (1940, p 664) in which a 0.3 mm displacement of isoclines of inclination (I) is shown to be equivalent to a 3 percent external contribution found in an analysis by Bauer (1923). In analyzing the vertical component of both U. S. and U.S.S.R. charts for 1955 Jensen and Whitaker (1960) noted differences of up to 6 percent in some regions. Ivanov (1961) in reporting on "Zarya" measurements noted regions where the errors in the U.S. charts for Z exceeded 2000 gammas, approximately 8 percent. Ivanov (1961) also states that the discrepancies between U.S. charts for the total scalar field, F, and the "Zarya" measurements amount to 1500 gammas in almost the entire Southern Hemisphere at latitudes less than 40 degrees and speculates that the errors are probably greater at higher latitudes. The "Zarya" in general showed better agreement with the British Admiralty charts in the Atlantic and Indian Oceans at latitudes less than 40 degrees. Errors in the British charts approached 1 degree in declination and 500 gammas in intensity in the Northern Hemisphere and 2 degrees and 1000 gammas in the Southern Hemisphere.

The data limitations also explain why the assumption of a constant radius, r = a, which neglects Δr's of 1 part in 297 from earth oblateness as well as topographical differences, has had little, if any, influence on results.

3.B. Recent Analyses Using F and Space Data:

The need for methods of analysis utilizing total scalar magnetic intensity (F), rather than component intensities appeared about 1957 when it became apparent that data from future satellites would be primarily scalar as a consequence of the instruments to be used and even more important the difficulties of achieving the accurate reference directions required for component measurements. Zmuda (1958) first

illustrated that the Gaussian coefficients g_n^m, h_n^m for internal sources appearing in

$$V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} P_n^m (\cos \theta) \left[g_n^m \cos m\phi + h_n^m \sin m\phi\right] \quad (10)$$

were obtainable through analysis of F^2 by squaring the series for each component X, Y, and Z and adding the terms, thus obtaining a series for

$$F^2 = X^2 + Y^2 + Z^2 \tag{11}$$

As illustrated for an eccentric dipole model the first eight harmonics, through $n = 2$, $m = 2$, give 31 new coefficients representing combinations of the eight desired. Although 31 coefficients is a considerable reduction from the 93 obtained without addition it is apparent that the series becomes immense in higher degree representations such as $n = 6$. Zmuda (1958) further treated the problem of separating internal and external sources but here made an error in assuming that a scalar subtraction of fields due to internal and external sources was a valid simplification.

Jensen and Cain (1962) using expressions (10) and (11) and considering internal sources only, such that the coefficients of (5), (6), and (7) become the Gaussian coefficients g_n^m, h_n^m, devised a method to determine the coefficients which avoids the nonlinear dependence of F^2 (or F) on g_n^m, h_n^m and permits the use of least squares fitting to the data. The method is one of improving on an existing set of coefficients without being dependent on the existing set being very accurate. The procedure is to expand F^2 into a Taylor series that includes only the linear term, giving

$$F^2 = F_0^2 + 2 \sum \left[u_n^m (\Delta g_n^m) + v_n^m (\Delta h_n^m)\right] \tag{12}$$

where

$$u_n^m = \left(\frac{a}{r}\right)^{n+2} \left[Z_0 \, (n+1) \, (\cos m\phi) \, P_n^m \, (\cos \theta) - X_0 \, \cos m\phi \, \frac{dP_n^m \, (\cos \theta)}{d\theta} \right.$$

$$\left. + Y_0 \, (m \sin m\phi) \, \frac{P_n^m \, (\cos \theta)}{\sin \theta} \right] \tag{13}$$

and

$$v_n^m = \left(\frac{a}{r}\right)^{n+2} \left[Z_0 \, (n+1) \, (\sin m\phi) \, P_n^m \, (\cos \theta) \right.$$

$$- X_0 \, \sin m\phi \, \frac{dP_n^m \, (\cos \theta)}{d\theta} \tag{14}$$

$$\left. - Y_0 \, (m \cos m\phi) \, \frac{P_n^m \, (\cos \theta)}{\sin \theta} \right]$$

Values for F_0, Z_0, X_0, and Y_0 are computed at the data locations using the best available set of coefficients g_n^m and h_n^m. The Δg_n^m and Δh_n^m are the corrections made to the initial g_n^m and h_n^m to obtain the best fit to the measurements. The summation term in (12) given by

$$E = F^2 - F_0^2 \tag{15}$$

indicates the error, or residual between measured and computed values, and as this term is linear with respect to the Δg_n^m, Δh_n^m a least squares fitting can be used to find the corrections and thus generate an improved set of coefficients. In application the process is one of successively applying the corrections and repeating the procedure until

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significant improvements in accuracy are no longer obtained. The procedure also applies to the components and can be used to mix component and total field data (e.g., for the horizontal intensity H one has $E = H^2 - H_0^2$).

The method of minimizing $F^2 - F_0^2$ was first applied to approximately 3000 measurements of the scalar field taken by Vanguard-3 between latitudes ± 33.5 degrees and altitudes 510 to 3753 km. Although this produces a good fit it automatically weights the data using least squares by the factor $(F + F_0)^2$ as seen by rewriting the squares as

$$\sum (F^2 - F_0^2)^2 = \sum (F - F_0)^2 (F + F_0)^2 \tag{16}$$

which emphasizes the data at low altitudes and high latitudes relative to the high altitude and low latitude data. As the difference between $2F$ and $F + F_0$ is negligible in a weighting sense the weighting factor can be removed by minimizing the error quantity

$$E = \frac{F^2 - F_0^2}{2F} \doteq F - F_0 \tag{17}$$

in place of (15). Another alternative is to minimize the fractional (or percentage) error given by

$$E = \frac{F - F_0}{F} \tag{18}$$

This has the effect of weighting the high altitude or low latitude data more heavily than the low altitude or high latitude data.

In subsequent analyses of Vanguard-3 data (Cain, et al., 1962b) all three expressions (15), (17), and (18) were used with comparable results. Average residuals vs. altitudes from use of (15) and (18) are shown in Figure 4. The series involved 63 coefficients, g_n^m and h_n^m with n and m of 7, which, as an example taking expression (18), fitted all data (disturbed as well as quiet days) with a root mean square residual of 21 gammas or 0.13 percent. Of this 12 gammas could be attributed to errors of measurement coming primarily from orbit position errors. The remaining 9 gammas was easily attributed to disturbance effects. In contrast use of the initial Finch and Leaton (1957) coefficients on the same data gave an r.m.s. residual of 255 gammas. Thus the method worked well for this limited case which represents strictly a curve fitting procedure not taking into account the existence of external sources and not attempting to fit data outside the regions of measurement. The coefficients for this special analysis of limited regions over North and South America, the Caribbean, Australia, and South Africa are given by Cain, et al. (1962a).

The method was next applied by Jensen and Cain (1962) using expression (17) and the H equivalent, to a collection of 74,000 values of F and H taken since 1940 of which about 28,000 points were F measurements from aerial surveys, 3000 points were F measurements from Vanguard 3, and the remainder were surface values for H. To shorten the time for each iteration only every tenth point was used in the computation of coefficients. The fit was made to the year 1960 with the assumption that secular variations could be approximated by a linear time dependence. This was included by substituting coefficients Δg_n^m + $(t - 1960) \Delta (d g_n^m /dt)$ and $\Delta h_n^m + (t - 1960) \Delta (dh_n^m /dt)$ for Δg_n^m and Δh_n^m in expression (12). The accuracy achieved as indicated by the residuals was closely related to the distribution of data, giving root mean square errors of: 135 gammas in regions of good coverage, about 600 gammas in regions of poor coverage, and 304 gammas for the total data. As a check on the method, computed values were compared with U.S. chart
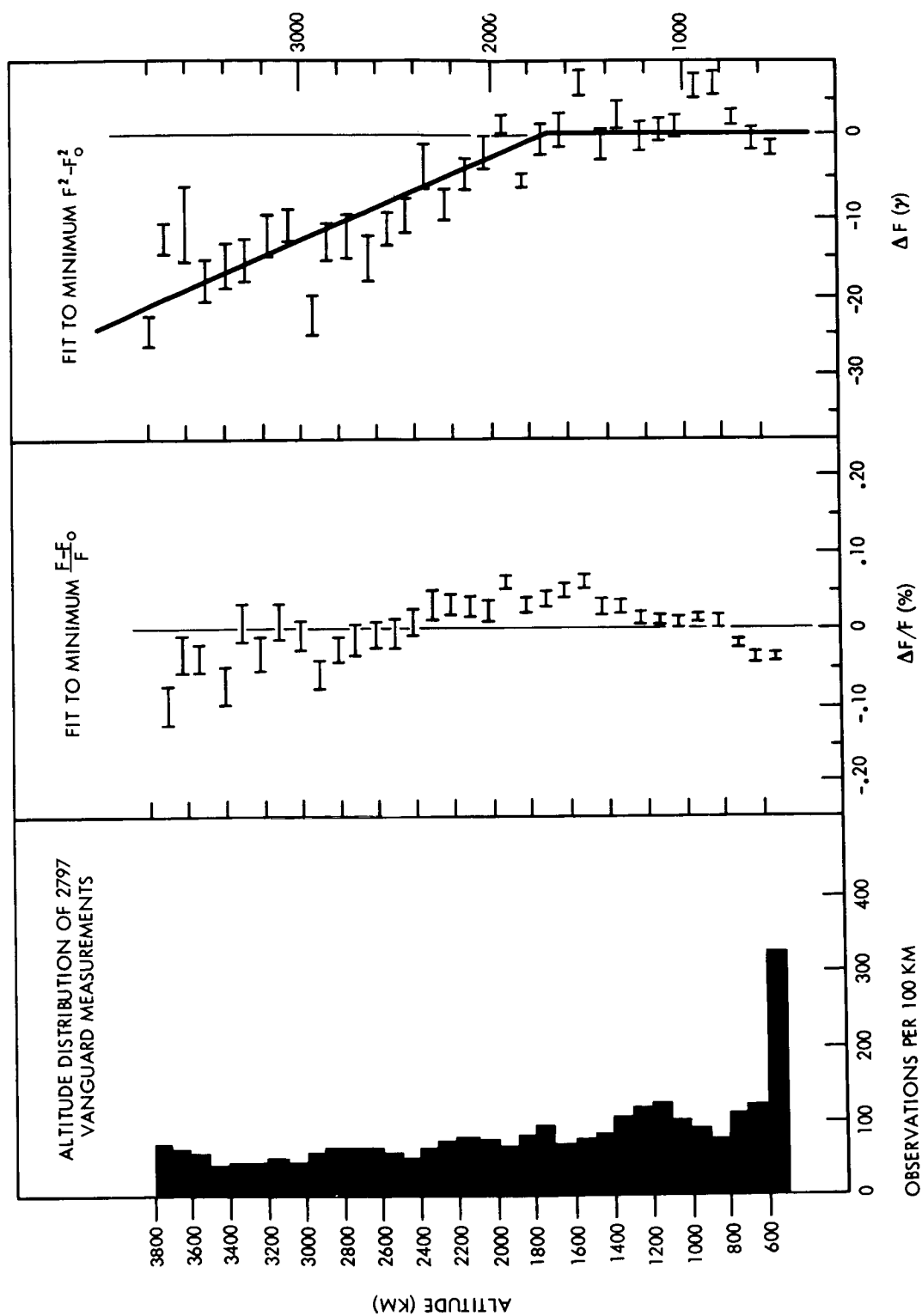
Figure 4—Average residuals of Vanguard 3 data relative to two different, m = n = 7, spherical harmonic reference fields as a function of altitude. Error bars show the standard errors of the mean residuals.

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values along parallels of latitude and in general closer agreement was achieved by using the new coefficients than by using the Finch and Leaton (1957) coefficients which were used for the initial g_n^m, h_n^m. Although the Jensen and Cain method worked well, major improvements over past analyses could not be expected using the existing data.

Comparing also the relative magnitude of the residuals in fitting just Vanguard data and fitting the more heteorogeneous set of surface data, one gets some indication of the refinements in analysis than can be expected from future satellite data relative to handling data from the earth's surface where local anomalies have a major influence.

3.C. Questions Regarding Field Sources and the Number of Coefficients

It is commonly believed that sources of the field interior to the earth's surface are confined to two regions: a primary region located in the earth's core (depth > 2900 km), and a secondary region, the earth's crust. There is also considerable evidence (Serson and Hannaford, 1957; Alldredge and Van Voorhis, 1961; Alldredge, et al., 1963) that the sources in the crust most typically have linear dimensions of less than 50 kilometers and the number of occurrences of anomalies with greater dimensions decreases rapidly with increasing dimensions up to several hundred kilometers. Anomalies with dimensions greater than several hundred kilometers appear to be very rare. Thus any attempt to represent typical crustal sources in a global spherical harmonic description would be ridiculously cumbersome and these "local" anomalies are more properly treated as noise. It should, however, be noted that strike-slip fault displacements of magnetic anomaly patterns of 1420 kilometers have only recently been found by Vacquier, et al. (1961) and it is not inconceivable that major geologic features still unknown may contribute to future descriptions. Similarly the available data does not completely rule out the possibility that

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crustal differences between oceans and continents may have an influence in future analyses. If we ignore these latter possibilities for the time being, the question then is "how many coefficients are required to describe the interior field as observed at and above the earth's surface, exclusive of crustal anomalies?" The question has direct physical significance in understanding the hydromagnetic dynamics of the core. Although a unique determination of interior sources is not possible with surface measurements, it is partly on the basis that coefficients of higher degree and order than $n = m = 6$ have historically been unnecessary that the belief has evolved that sources of continental dimensions and sources in the mantle are essentially non-existent. There are of course physical reasons as well for assuming an absence of primary sources in the mantle (see e.g., Elsasser, 1950).

Strictly from an analysis standpoint there are grounds for questioning the ultimate adequacy of an $n = m = 6$, or 48 coefficient, representation. Jensen and Whitaker (1960) for example found that higher order terms were not insignificant in their analysis and permitted the computer to run through $n = 24$, $m = 17$, producing 512 coefficients at which point one percent contributions were still being obtained. They concluded quite logically that the large number of coefficients merely reflected the chart errors as the analysis technique assumed a perfect chart. Similarly, Fanselau and Kautzleben (1958) carried an analysis through $n = m = 15$ and reached the conclusion that beyond $n = m = 6$ the data was too inaccurate to obtain an improvement in the description. This point is simply seen in a rough way by noting the agreements and disagreements between the signs of the three sets of coefficients in Table 1 which were derived from three different data sources. Through $n = 4$ all signs agree; for $n = 5$, three sign disagreements are noted in the 11 coefficients; for $n = 6$, seven sign disagreements appear in the 13 coefficients. It appears logical to conclude that the $n = m = 6$ cut-off point in past global analysis is imposed by the data and is not necessarily determined by the real form of the field.

Table 1: Values of g_n^m, h_n^m to n = m = 6 from Several Analyses

n	m	Jensen and Whitaker Year 1955*		Finch and Leaton Year 1955		Jensen and Cain Year 1960	
		g	h	g	h	g	h
1	0	30396		30550		30411	
1	1	1955	-5677	2270	-5900	2147	-5799
2	0	2331		2280		2404	
2	1	-5007	3133	-5250	3290	-5125	3312
2	2	-1444	-398	-1370	-210	-1338	-158
3	0	-2946		-2950		-3152	
3	1	5672	1346	5860	1380	6213	1487
3	2	-2181	-407	-2440	-570	-2490	-408
3	3	-788	37	-720	80	-650	21
4	0	-3849		-4150		-4179	
4	1	-4292	-427	-4400	-820	-4530	-1183
4	2	-2307	876	-2270	1210	-2180	1001
4	3	770	296	800	80	701	43
4	4	-269	144	-230	120	-204	139
5	0	1402		2090		1626	
5	1	-3925	60	-3220	-170	-3441	-80
5	2	-990	-688	-1550	-750	-1945	-200
5	3	465	-82	170	230	-61	460
5	4	237	195	340	310	278	242
5	5	19	-39	50	-60	70	-122
6	0	-55		-1500		-1952	
6	1	-1515	695	-930	440	-485	-576
6	2	-1336	-1972	-250	-1660	321	-874
6	3	1833	346	2410	-40	2141	-341
6	4	208	262	160	60	105	-12
6	5	-34	-58	-10	60	23	-112
6	6	37	31	70	10	112	-33

*Continues to n = 24, m = 17.

Thus for clues to the answer regarding the number of significant coefficients, prior to analysis of WMS data, we have to look at analyses of measurements that are restricted in distribution but are at least homogeneous in quality and taken within a time span that does not involve large uncertainties caused by secular variations. Alldredge, et al. (1963) have attempted to do this by piecing together flight tracks from Project Magnet to simulate a single around-the-world, roughly great circle, magnetic profile. Using F rather than components for reasons of accuracy and completeness, harmonic coefficients in a Fourier series were computed up to the 2000th order. The amplitude of the coefficients dropped off rapidly up to order 7. Beyond the 6th order, the envelope of the coefficients slowly decreased in amplitude to a value of about one gamma for the 2000th harmonic. The break above the 6th order coefficient was attributed to the separation of core and crustal sources. The authors noted that roughly 4 million spherical harmonic coefficients would be required to similarly represent crustal anomalies over the entire earth and proceeded to estimate the number of spherical harmonic coefficients required to represent core sources under the assumptions that the single profile was representative of all great circle profiles and smoothing over 400 km distances would effectively remove crustal sources. Determining the number of coefficients required to represent F^2, as opposed to F in Fourier analysis, was used as a basis for relating the Fourier and spherical approximations and an intermediate analysis was performed to reduce truncation errors. For these assumptions the authors concluded that spherical harmonic coefficients of $n = m > 10$ are probably not required to describe the earth's main field caused by interior sources. The break near $n = 10$ is illustrated in Figure 5.

Vanguard 3 provides another homogeneous, but restricted in distribution, set of data for approaching the above question. Heppner, et al. (1961) illustrated the systematic shift of curves for $\Delta F = F$ (measured) $-F$ (computed) over several degrees of latitude in the region of Australia at altitudes > 510 km (perigee). At perigee, the changes
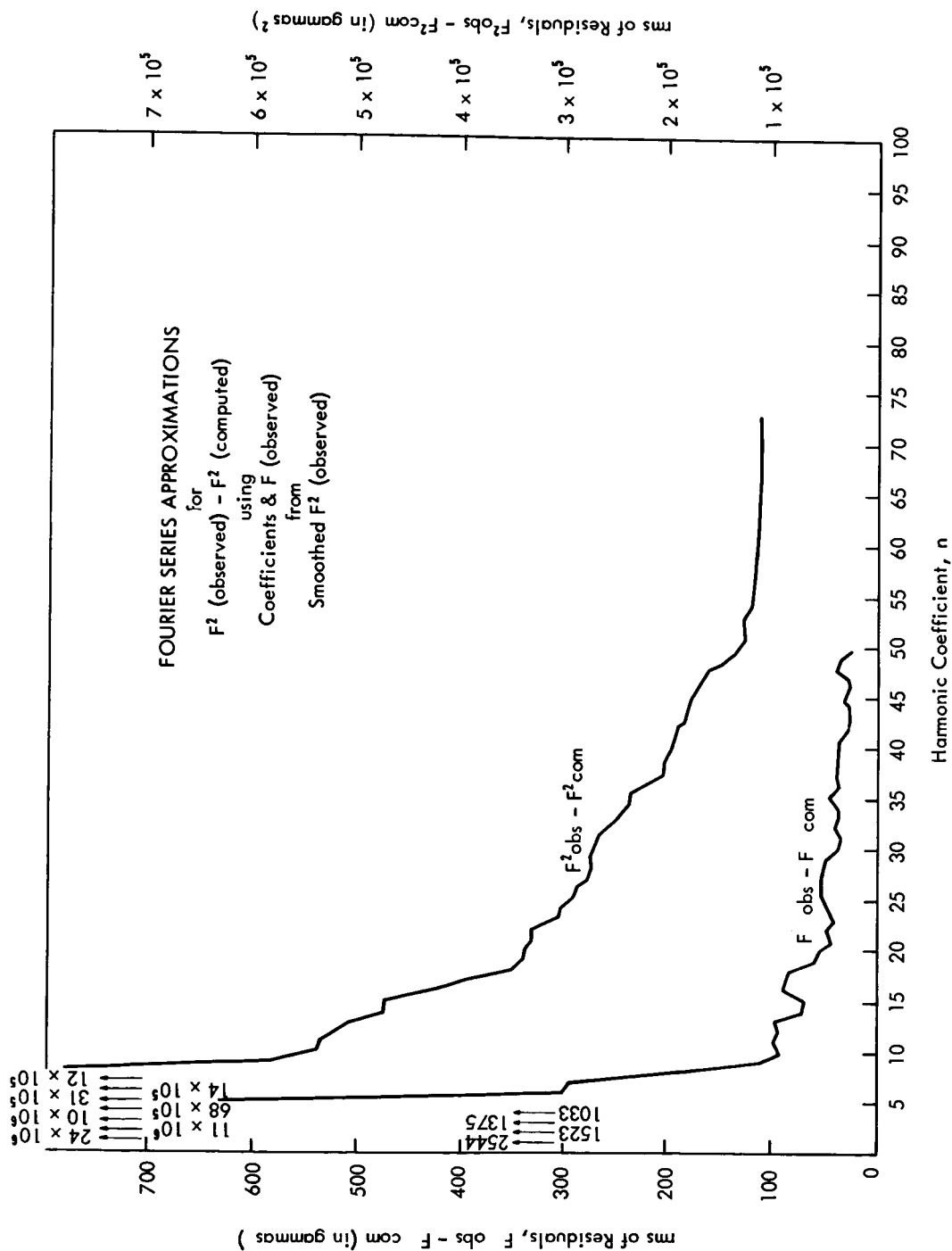
Figure 5—Analysis of a composite Project Magnet around-the-world field track by Alldredge, et al., (1963). RMS residuals of F as a function of order of harmonic coefficients for a Fourier series field fit to F^2.

in ΔF approached 0.4 and 0.3 percent, respectively, for Jensen and Whitaker (1960) and Finch and Leaton (1957) coefficients between approximately 25 and 33 degrees south latitude. In this region the percentage change in ΔF with latitude also decreased rapidly with altitude. This behavior was interpreted in terms of internal sources with a rough estimate that harmonics of degree 20 would be required to match the data. The $n = m = 7$ analyses of just Vanguard data (see Sec. 3.B.) reduced the shift noted above to 0.1 percent but these analyses necessarily put great emphasis on the specific area in question relative to the rest of the world. The possibility exists that the rapid change in ΔF with latitude and altitude could have been caused by a diurnal effect (perigee data was available for night hours only) but the magnitude is incompatible with diurnal variations observed at the earth's surface.

Examination of Vanguard-3 data for much smaller effects than that noted above also leads one to conclude that it is potentially possible to describe the field to an accuracy greater than that permitted by a 63 coefficient, $n = m = 7$, representation. Figure 4, for example, shows systematic behavior with altitude despite the smallness of the residuals and it was not found possible (Cain, et al., 1962) to eliminate the altitude variation using internal sources only. The negative slope above 1800 km (Figure 4) was present in all data fittings as was the negative displacement in the 500 to 800 km range. Although the distribution of measurements with altitude and local time did not permit Cain, et al., (1962) to definitely conclude that this was not a diurnal effect, interpretation in terms of existing theories of diurnal variations and their surface behavior was not promising. A simple alternative, at least until external sources are better understood, is to: (a) attribute most of the negative effect above 1800 km to the influence of external sources in and above the region of measurement, and (b) attribute the negative shift below 800 km to inadequate description of the internal sources with an $n = m = 7$ approximation. In detail the negative behavior between 500 and 800 km comes primarily from effects near-perigee in

the regions of southern Australia noted above, and an area centered on the southwest corner of the U.S. If explanation (b), above, is correct it suggests that the estimate made by Alldredge, et al. (1963), that n = m = 10 should be sufficient for internal sources, may be too low.

4. WMS Satellites: General Considerations and the POGO System

4.A. Orbit Selection

Orbits will be discussed here in terms of optimum orbits for meeting the basic WMS objectives. Thus, highly eccentric orbits and/or circular orbits at great distances which are primarily intended for magnetospheric studies will be ignored because they provide relatively little information on the detailed form of the field from interior sources. It should however be recognized that they have considerable importance in determining the distribution of external field sources. Similarly, considering coverage rather than altitude, orbits of low inclination are certainly not in the optimum category for the WMS.

The desirability of having a highly inclined orbit plane, preferably passing close to the poles, is obvious. The need for latitude coverage comes not only from considering the analysis of satellite data but also from the consideration that surface data is very sparse and difficult to obtain in the high latitude regions — especially in the Southern Hemisphere.

If all magnetic field sources were interior to the earth's surface the orbit having the lowest possible altitude would be optimum for the WMS. "Lowest possible," however, still means an altitude that would provide adequate lifetime for achieving the desired global coverage. It also means an altitude at which variations in satellite drag are sufficiently

small to not introduce significant errors in the determination of the instantaneous location of the satellite at the time of each field measurement.

The question "what is an adequate lifetime and/or coverage?" has two quite different answers with the choice depending on the importance attached to removing possible effects of diurnal magnetic variations. The first answer either neglects diurnal effects and hopes that they are negligible or assumes that they can be removed in analysis using independent surface observations in conjunction with a theoretical model for their cause. For this answer, for a polar orbit, one is concerned with the choice of the local time zone of the orbit plane but treats the lifetime solely in terms of the rate of measurement and longitude differences in equatorial crossings to arrive at a measurement grid with some minimum spacing between points. The IUGG manual, Vestine (1961), for example, suggests a minimum density of readings each 100 km along the orbit and equatorial crossings separated by a maximum of 400 km. Assuming that the orbit period does not have an integral multiple giving 24 hours, which would give equatorial crossings at the same longitudes on successive days, a grid of this density is easily achieved in several weeks. The exact lifetime depends of course on the orbit period and what portion of the data is considered questionable for mapping because of magnetic disturbance. The second answer comes closer to perfection by assuming that the diurnal magnetic variations are not negligible and similarly that corrections based on theoretical models for their cause may be grossly erroneous. In this case satellite passes through all local time zones are needed and this requires a lifetime of 6 months.

Next, to be optimum the orbit should have characteristics which simplify the problem of separating internal and external sources. Here one is concerned, relative to existing knowledge, with external sources having world wide effects such as those of magnetospheric compression by the solar wind and trapped particle drifts and diamagnetism. There is considerable evidence that these external sources contribute at

least 20 to 50 gammas, and possibly more, to the average surface field. In global descriptions the external field effects have obviously been hidden in the limitations of past analysis (Section 3) but they will assume importance in future analysis anticipating a factor of 10 improvement. It is apparent that the resolution in separating the terms $(a/r)^{n+1}$ and $(r/a)^n$ in equation (1) is improved considerably when satellite measurements are available at different altitudes. Thus, Kalinin (1961) suggested that two satellites in circular orbits of different altitudes should be used for the WMS. As noted in the POGO discussion below, a range of altitudes can also be obtained at all latitudes using only one polar satellite provided the orbit is eccentric. One is then faced with the question of an optimum apogee altitude, assuming that a choice of low perigee has been made in accord with the previous discussion. Ideally to get maximum resolution in separating sources one wants the apogee altitude below but approaching close to the altitude of the lowest altitude external source of significance. Conversely one does not want apogee so high that sensitivity to the high order internal terms is lost, particularly if the operating lifetime is shortened by failures. Obviously compromises and assumptions become necessary in picking apogee. For example, from the discussion of Vanguard data in Section 3.C. one might assume a maximum apogee of less than 1800 km for staying below significant external sources and less than 800 km for maintaining sensitivity to interior sources of high order. Similarly one might assume that there was merit in staying below the intense regions of the inner radiation belt (i.e., < 1200 km). There is not an obvious select altitude but there are good reasons for keeping apogee in the range of several hundred kilometers above perigee to altitudes less than 2000 km and additional arguments for placing apogee below 800 km if the operating life is short compared to the time it takes for perigee and apogee to move roughly 180 degrees in latitude.

Without going into detail it is apparent that analogous problems are encountered in Kalinin's (1961) suggestion of two circular orbits; for example, in picking the altitude of the highest orbit and in

considering the consequences of an early failure in either of the two satellites.

In summary the above depicts the most favorable single orbit as an orbit with the following characteristics: polar inclination, a minimum lifetime of 6 months, perigee as low as possible subject to the lifetime requirement, and an apogee altitude, less critically defined, but located at least several hundred kilometers above perigee and less than 2000 kilometers altitude. There are various other orbits which could give more definitive results pertaining to isolated WMS objectives but these could not individually meet the overall objectives as well as the orbit described above. Further improvements can of course be obtained using two or more satellites in orbits selected to complement each other.

The POGO orbit parameters, as currently planned, are: inclination between 82 and 90 degrees, 250 km perigee, 925 km apogee, and an active life that will approach one year if there are not critical failures. The fact that these characteristics are favorably matched to the optimum single orbit described previously is partly circumstantial in that the initial selection of altitudes for POGO was primarily the result of other considerations such as a favorable altitude range for a variety of aeronomy experiments.

Figure 6 illustrates the retrograde motion of perigee in days as a function of latitude and local time for two orbits which are roughly similar to orbits planned for POGO. The assumption of satellite injection, or 0 day, at 06 hour is arbitrary. The equivalence to having a low altitude circular orbit, and a number of higher circular orbits, is evident by noting that within 49 and 58 days, respectively for 90 and 80 degree inclinations, perigee has moved over the entire range of north and south latitudes. An additional feature of a non-circular orbit, pertinent to the external source problem, is that measurements are obtained at two altitudes each day with the exceptions of polar regions and times when the apsides are at maximum inclination.
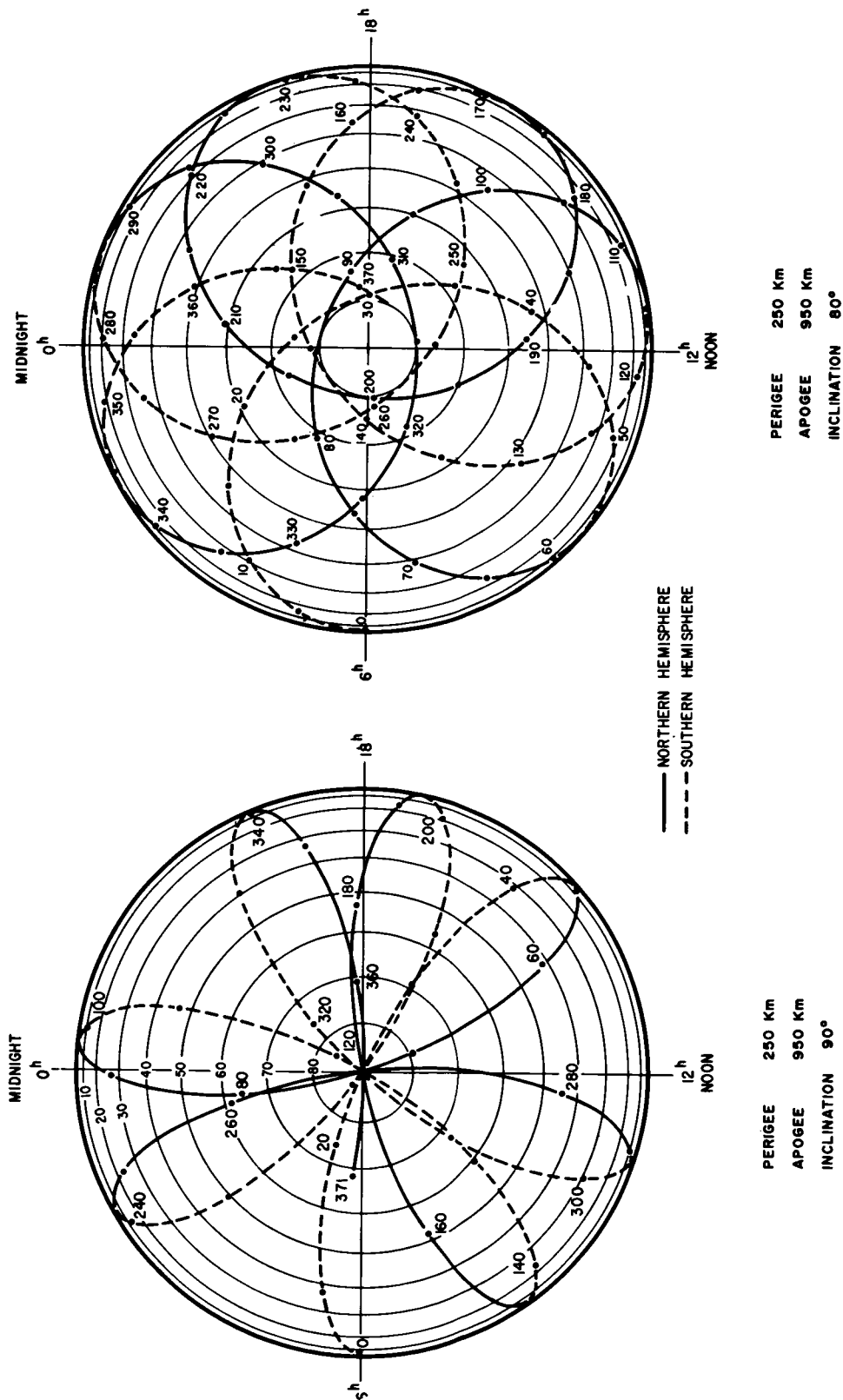
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Figure 6—Latitude and local (solar) time of perigee point as a function of days after satellite injection for two orbits similar to the POGO orbit. Local time of injection is arbitrarily taken at 06 hours. Days following injection are noted at 10 or 20 day intervals.

4.B. Location Accuracy

Knowing the exact space location (latitude, longitude, and altitude) at the time of each field measurement is one of the most critical problems for the WMS. The instantaneous location of the satellite must be known with errors < 1.0 km horizontally and < 0.25 km vertically to be consistent with the objective of maintaining maximum field errors from all sources below 10 gammas. This assumes that all other sources of error are small relative to the errors created by the displacement between the true location and the computed location.

Location errors have, in general, been difficult to estimate in an absolute sense because the estimates are usually based on relative agreement between independent determinations. Confidence is developed primarily by finding agreement between determinations employing different types of tracking data. When the satellite is also making absolute magnetic field measurements there is an additional check on the daily, weekly, or monthly precision of the orbit analysis as illustrated by Heppner, et al. (1960a, 1960b) for Vanguard 3. The critical evaluations of the Vanguard 3 orbit determinations (see Cain, et al., 1962a, 1962b) illustrate the problem as they are based on both optical tracking and minitrack, radio interferometer, tracking and have the additional feature that they were checked against field measurements and subsequently re-evaluated a number of times to remove obvious discrepancies. The results show that the WMS objective would not be met using tracking and analysis techniques similar to those of Vanguard 3.

An important step toward solving this problem in POGO is the inclusion of a two-way doppler, range and range rate, tracking system to supplement the standard radio interferometer, Minitrack, tracking system. This combination of distance, velocity, and angle measurements is expected to provide the required accuracy. Early flight tests of the range and range rate system have for example shown precisions equivalent to maximum errors of several tens of meters. There are,

however, other considerations in addition to tracking errors, such as: (a) relative time errors between stations, (b) errors in knowing the exact geodetic location of each station, (c) errors which will vary with satellite location and/or time coming from inaccuracies in knowing or accounting for small differences in the gravitational acceleration, satellite drag, radiation pressure, and in some systems, the propulsion effects of satellite orientation controls, and (d) errors in the methods of analyzing tracking data and computing instantaneous positions over the entire earth when tracking data is available from only a small number of stations. Cumulatively, these considerations cast doubt on any anticipation of maintaining maximum errors well below 10 gammas in a low altitude orbit. Thus, it is likely that location errors will be the limiting factor in the accuracy of the WMS Satellite data.

4.C. Scalar or Vector Measurement Question

A question which has frequently appeared in discussions of the WMS is whether or not the satellite scalar total intensity measurements will be adequate for obtaining a vector description of the field. As the potential derived from scalar measurements in a source free region is unique (See, e.g., proof by Jensen, 1962) the question is primarily directed toward the computational feasibility. What little experience there is to date does not suggest that the scalar analysis involves inherent difficulties. In fact, the analyses of Jensen and Cain (Section 3.B.) suggest that the question of scalar or vector measurements is not particularly critical. This may, however, be partially a consequence, and perhaps a merit, of the method in that an initial field based on vector information is used as a starting point. Conversely an initial field based on a previous scalar analysis could also serve as a starting point so this can hardly be considered an essential feature at present. It should, however, be recognized that the fields derived from scalar values have to date only considered internal sources and adequate attempts to compare analyses under conditions of external field

sources have not been made. Such comparisons would also be relatively meaningless using existing data.

The question is also equivalent to asking whether or not the coefficients derived from the scalar field, F, will give convergence to a higher, equal, or lower noise level, or magnitude of residuals, than a set of coefficients derived from X, Y, Z, or equivalent angle and component measurements. Thus the question in a practical sense is related to the relative accuracy of scalar and component measurements from a low altitude satellite.

Absolute accuracies of a fraction of a gamma to several gammas, depending on the particular system, are readily achieved with nuclear and atomic resonance magnetometers measuring the scalar intensity. It is more difficult to estimate an accuracy for component measurements because a number of variables have to be considered, such as: (a) the accuracy of the magnetometer measuring components or angles, (b) the accuracy of knowing the orientation of a coordinate system at the magnetometer relative to the coordinates of the satellite system providing measurements of the satellite orientation, and (c) the accuracy of measuring the satellites orientation relative to earth coordinates.

A proper review of item (a), which would consider various possible magnetometer systems many of which are in turn dependent on the type of satellite motion, would be unduly long. The use of flux-gate, or second harmonic saturable core, magnetometers is well known: for component airborne measurements (Serson, 1960; Schonstedt and Irons, 1955), for scalar field rocket measurements (Maple, et al., 1950; Singer, et al., 1951), for scalar field satellite measurements (Dolginov, et al., 1960, 1961, 1962). Although item (c), above, would not permit useful vector measurements in the rocket and satellite measurements noted above, the system descriptions (especially Dolginov, et al., 1962) illustrate many of the problems in past systems. Recently Heppner and

Boroson (1962) have demonstrated the feasibility of a new technique using fluxgates that is inherently simple in satellite application and is at least as accurate at near-earth field intensities as any fluxgate system known to the reviewer. Over the field range of the POGO orbit, magnetometer accuracies ranging from 20 to 60 gammas could nominally be expected. To reduce component measurement errors significantly below these figures it would probably be necessary to use a system involving the application of bias fields to an atomic resonance, optical pumping, magnetometer in a manner similar to the method described by Shapiro, et al. (1960) for a vector proton magnetometer. The accuracy in a low altitude satellite system would depend on the time interval between successive bias field reversals and having negligible changes in satellite orientation within these time intervals. The system requirements are not simple and further elaboration here is not justified in view of the likely errors from items (b) and (c) in satellite systems such as POGO.

Item (b), relating magnetometer coordinates to the coordinates of attitude sensors, is a matter of mechanical rigidity which might not appear to be a fundamental problem. Consider however, that a factor of ten improvement in describing the earth's field requires an angle accuracy of about 0.1 degrees (roughly equivalent to component errors of 0 to 50 and 0 to 100 gammas depending on the component and latitude as noted in Section 2.C.). For this accuracy the mechanical rigidity requirement would not be severe in a highly specialized non-magnetic satellite in which the magnetometer to satellite body separation was small. However, with separations requiring long booms, such as the 6 meter booms on POGO, the rigidity problem very definitely becomes fundamental and making this source of error a fraction of the total 0.1 degree error requires either a mechanical assembly of large weight or an auxiliary orientation sensing system relating the two coordinate systems.

Item (c), measuring the satellites orientation relative to earth coordinates, presents a major problem. There is not (to the reviewer's knowledge) any precedent in terms of satellites flown for measuring satellite orientation in all three coordinates with errors <0.1 degrees, especially under conditions that can be related to a polar orbiting satellite passing alternately in and out of the earth's shadow. For three axis data, reference to two bodies is required. Horizon and solar sensing combinations such as those in the OGO satellites (Ludwig, 1963; Scull and Ludwig, 1962) can provide measurements with errors less than 2 degrees when sensor error signals are analyzed but are inherently limited to minimum errors of 0.5 degrees by horizon variability. Looking beyond the existing art to future systems there are several possibilities, such as: (1) a satellite similar to the Orbiting Astronomical Observatory (OAO) with active, star tracking, pointing control but modified to include accurate optical measurements in the roll plane, and (2) spin stable satellites designed for negligible torque influences over several orbits and utilizing optical sensors having sharp resolution in recognizing the edge of the solar disc and a particular wavelength at the earth's horizon.

The additive nature of errors makes each of the problems noted above more severe than indicated. Solutions are in principal feasible in terms of known technological capabilities but in practice the extensive effort required to achieve vector accuracy has to be weighed against what is more easily achieved with scalar measurements. Thus when it is not obvious that vector measurements of 100 gamma accuracy possess advantages over scalar measurements accurate to several gammas, the extensive effort does not appear justified. There is not, however, an ideal substitute for direct vector measurement and ultimately such measurements will be needed for confirmation and further refinements. Vector measurements in low orbits are also needed for studies of various field variations. Thus efforts to obtain vector measurements of high accuracy can be expected in the future.

4.D. Magnetometers

The characteristics of optical pumping magnetometers make them particularly well suited for the WMS satellite requirements for accuracy and in-flight data storage between command read-outs. To illustrate this preference for optical pumping magnetometers it is instructive to note the principal limitations of other types. Saturable core, second harmonic, magnetometers cannot be expected to meet the accuracy requirements for scalar measurements and their use for vector measurements would be very limited in satellites not having an appropriate direction reference system, as discussed in the previous section. Similarly, Hall generator and spinning coil magnetometers do not have sufficient accuracy. Proton precession, nuclear resonance, magnetometers of the free precession type, f_p (cps) $= 4257.6$ (F) with F in gauss, used in Vanguard 3 have the necessary absolute accuracy but difficult operational problems occur in data storage as a consequence of the low signal to noise ratio when a wide range of field intensities is to be measured. Solutions involve having either: (a) a high-Q selective filter that automatically adjusts to the precession frequency such that in-flight frequency measurements can be made relative to a higher frequency oscillator (See Heppner, et al., 1958, for an example) or (b) in-flight direct storage of the precession signal on magnetic tape for command playback. Technique (b) involves wasteful use of a high speed tape recorder which must also record a standard frequency signal such as 10 or 100 kc/s to achieve accuracy independent of variations in tape speed. Other disadvantages include: low information content per unit of power, and susceptibility to audio noise frequencies from spacecraft sources and natural whistlers and VLF emissions.

The magnetometers noted above have known operational characteristics that permit evaluation. There are other types of magnetometers to consider that fall in the category of being potentially suitable for the WMS but whose state of development does not permit

use in the earliest WMS satellites. One example is the nuclear reso-
nance, "maser" magnetometer described by Abragam, et al. (1962)
which utilizes the Overhauser effect between the magnetic moment of
an electron carried by a free radical and the magnetic moment of a
proton to produce a continuous signal at the Larmor frequency of the
proton, f_p = 4257.6 (F). The advantages relative to proton free preces-
sion, of greater signal strength and lower power input remove some of
the operational difficulties in using proton magnetometers. A problem
which has been critical, at least in the past, is obtaining samples in
which the free radical lifetime permits operation for long periods of
time. Another example, which shows promise as a result of observations
of the electron gyrofrequency by the Topside Sounder satellite, is a mag-
netometer based on phase locking a transmitter to either signals re-
ceived at a harmonic of the electron gyrofrequency or to a transmitting
antenna impedance characteristic occurring at a harmonic of the gyro-
frequency. The locked transmitter frequency, f (cps) = N (2.8 x 10^6) F,
with F in gauss and N designating the harmonic, can potentially provide
an extremely sensitive field measurement in regions of strong magnetic
fields and high electron densities like those occurring along the POGO
orbit.

Returning to the subject of optical pumping, atomic resonance,
magnetometers there are two types to consider: metastable helium and
alkali vapor. Of the various alkalis (Li, Na, K, Rb, Cs), rubidium and
cesium are the most favorable from the standpoint of the operating
temperature and the resonant line width for all m levels. Within the
United States developments have concentrated on rubidium. The Rb-
vapor magnetometer to be flown on the first POGO satellite for the
WMS is discussed in the next section. As metastable helium magnetom-
eters may be used in future magnetic survey satellites a brief discus-
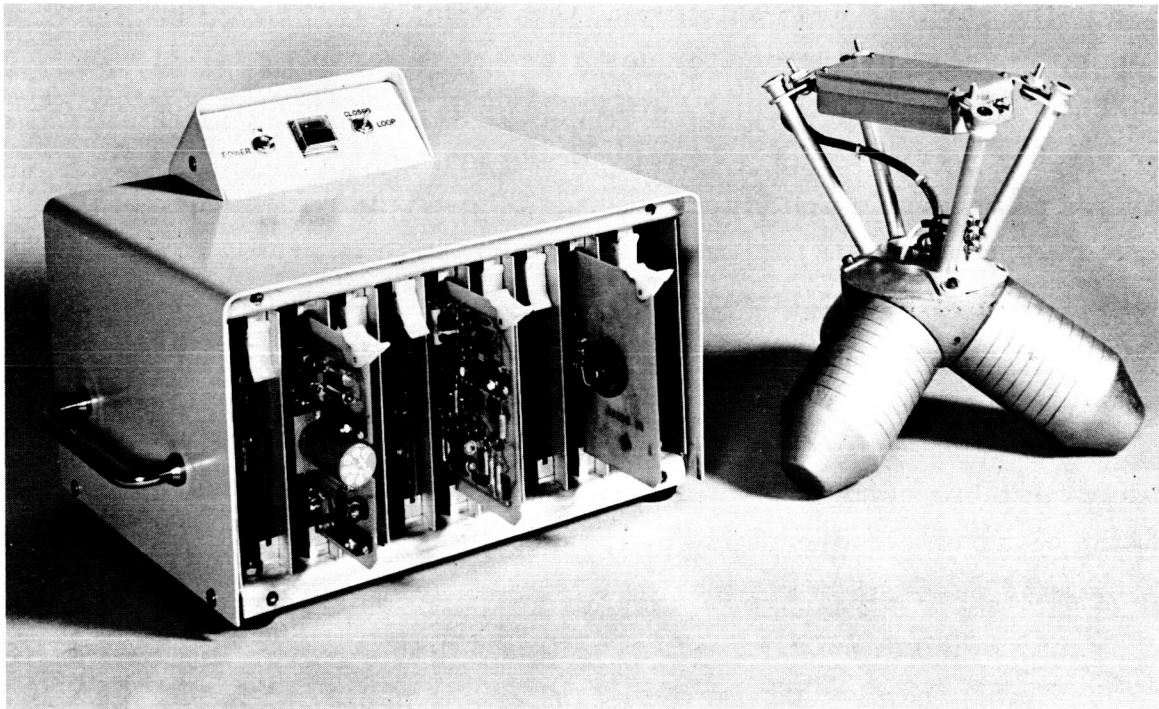sion is appropriate.

Figure 7—Prototype of a three axis, omni-directional metastable helium magnetometer

Figure 7 is a photograph of a prototype metastable helium magnetometer developed for the Goddard Space Flight Center by Texas Instruments, Inc. Three absorption cells, each with a circular polarizer, infrared detector, sweep coil, and cell exciting winding, are located along three orthogonal axes extending radially from a helium lamp which is driven by a 50 mc/s r-f oscillator following ignition by a high voltage. A preamplifier, to drive signals over a long boom cable, is located at the base of the lamp-sensor assembly. The lamp-sensor assembly is designed to fit in the same spherical enclosure on the POGO boom as the Rb-vapor lamp-sensor assembly discussed in the next section. Electronic units consisting of the r-f power oscillator, ignition circuits, amplifiers, servo sweep oscillator and phase lock circuits, and voltage controlled oscillator are located in the box shown. As demonstrated initially by Franken and Colegrove (1958) the Zeeman splitting (Larmor frequency separation) of a helium metastable energy level is such that the absorption of helium light near 10,830Å occurs at

different rates in the various Zeeman, m, levels. Application of a weak magnetic field at the Larmor frequency, approximately 28 cps/gamma (2.8 mc/gauss), produces a redistribution of electron populations in the Zeeman levels and light is absorbed at this resonant frequency. Helium atoms in the metastable state are continually provided by maintaining a weak discharge in the absorption cell. In an operational magnetometer an electronic servo technique, employing a sweep oscillator and phase detection, is used such that the frequency of a voltage controlled oscillator is continuously locked to the Larmor frequency. The oscillator output frequency thus provides the measurement of scalar magnetic field intensity. Orientation effects on the field value are small, about 2 gammas with 180 degree field reversal, but require compensation for high accuracy. Signal amplitude varies approximately as $\cos^2 \theta$ where θ is the angle between the optical axis and the magnetic field. This necessitates the use of three optical axes, Figure 7, and signal mixing in an instrument that is to provide measurements in all orientations.

Assessment of the relative advantages and disadvantages of metastable helium and rubidium vapor magnetometers is not intended here. It is obvious that the servo systems currently required in helium magnetometers, because of the frequency limitations of available infrared detectors, lead to a more complex electronic system than self-oscillating Rb-vapor magnetometers. On the other hand the wider temperature range for operation of a helium magnetometer without thermal control is a distinct advantage of the helium magnetometer. Similar considerations applied to weight, power consumption, susceptibility to errors, signal to noise ratio, reliability, etc. appear with advantages and disadvantages in each type. The most important single factor in selecting a Rb-vapor magnetometer for the first POGO satellite was the state of knowledge regarding operating characteristics in a space environment within spacecraft restraints.

4.E. POGO Magnetic Field Instrumentation

Descriptions of the series of satellites designated Orbiting Geophysical Observatories (OGO) which include the Eccentric Orbiting Geophysical Observatory (EGO) and the Polar Orbiting Geophysical Observatory (POGO) have been published by Scull and Ludwig (1962) and Ludwig (1963). These descriptions should be consulted for details involving the spacecraft system.

Both the EGO and POGO satellites carry Rb-vapor matnetometers with the lamp-sensor assembly enclosed in a 33 cm. sphere at the end of a boom extending 6.6 meters from the main body of the spacecraft. The external appearance of the EGO and POGO units is similar with the exception that the EGO sphere includes bias field windings and also carries a 3-axis fluxgate magnetometer located about two meters closer to the spacecraft. Figure 8, a photograph of the prototype of the EGO unit, is thus also representative of the POGO unit. The block diagram in Figure 9 illustrates the principal electronic units of the POGO magnetic field instrumentation.

The Rb-vapor magnetometer consists of two, self oscillating, double gas cell magnetometers which are individually similar to the type flown in Explorer-10 (Heppner, et al., 1963; Ruddock, 1961). The use of two units, placed in a crossed configuration as illustrated in Figures 8 and 9, greatly reduces the size of zones of field orientation where the signal to noise ratio is low. For each unit, signal amplitude is approximately proportional to $\sin 2\theta$ where θ is the angle between the field vector and the optical axis. This gives two regions of low amplitude: a conical region centered on the optical axis $(\theta = 0°)$ and a zone centered on a plane perpendicular to the optical axis $(\theta = 90°)$. Thus using two such units in an "X" configuration eliminates all orientations of low amplitude except where the two $\theta = 90°$ zones intersect to form two rhombic regions. The angle between the two optical axis is 55 degrees in the case of POGO. For nominal performance the size of these
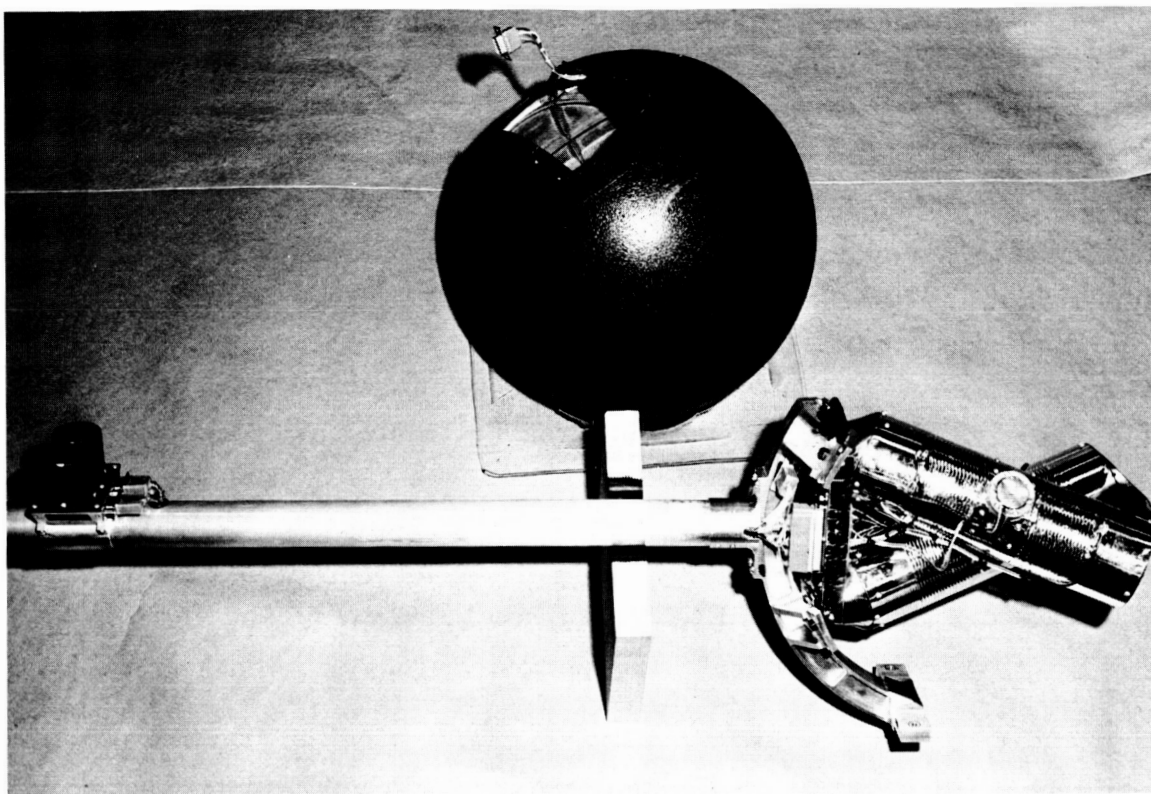
Figure 8—Prototype of an EGO boom mounted rubidium vapor magnetometer consisting of two double gas cell units. Radio frequency oscillators for lamp excitation are located on the boom to the left. The 33 cm. enclosing sphere is shown removed.
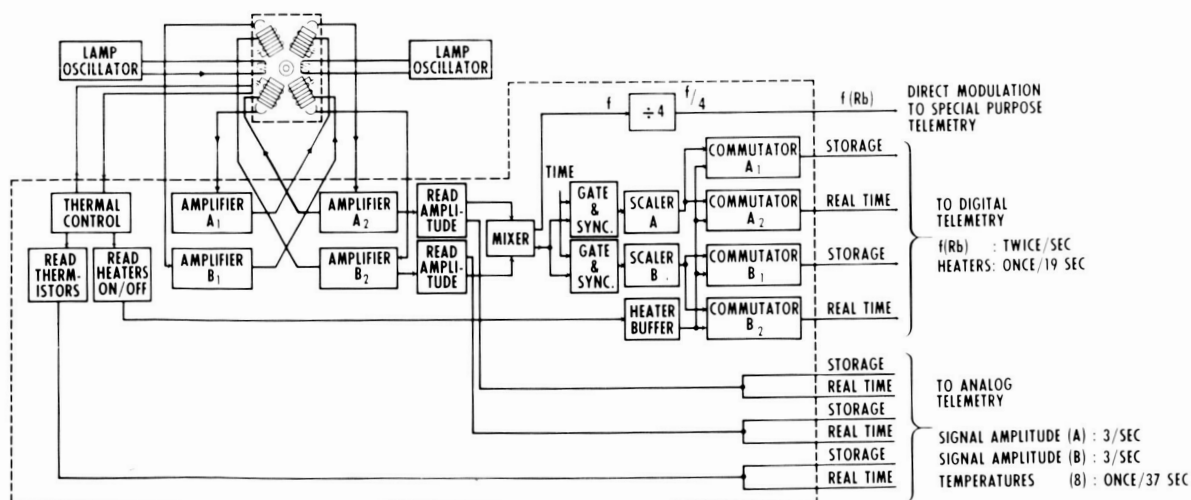

Figure 9—Functional block diagram of instrumentation for POGO magnetic field experiment

regions, determined by signal to noise for reliable frequency counting, is about 500 square degrees, each, or in total about 2.5 percent of the total spherical solid angle. The 2.5 percent loss region could of course be eliminated using a third optical axis but the complexity is not merited using double cell units. The use of three single cells, as described for helium in the previous section, is ruled out at the field intensities along the orbits of POGO for reasons of orientation errors, as noted below.

The Larmor frequencies for the rubidium-85 and -87 isotopes in a single gas cell, self oscillating, magnetometer are given by:

$$f \text{ (cps)} = 466744 \text{ (F)} \pm \text{(K)} \ 359 \ (F^2) \text{ for Rb-85}$$

and
$$f \text{ (cps)} = 699585 \text{ (F)} \pm \text{(K)} \ 216 \ (F^2) \text{ for Rb-87}$$

where F is in gauss, and K, usually < 0.4, indicates the fraction of the constant with the squared term that appears in a given instrument. As the F^2 dependence comes from the relative electron populations in the various m levels, which in turn depends on the field orientation relative to the optical axis, it is symmetrically $+$ and $-$ with respect to 180 degree field reversal. Thus by use of the double gas cell arrangement the F^2 dependence is eliminated and the field measurement is independent of orientation (see Ruddock, 1961, and Bloom, 1962 for further details). The choice of isotope, 85 or 87, is not critical. Rubidium-85 will probably be used on the first POGO for reasons of signal to noise as limited by the high frequency response of the silicon cell light detectors in fields approaching 0.65 gauss.

To decrease the probability of a single failure causing a total loss of data the design is oriented toward achieving redundancy within the restrictions of weight and power. Thus (see Figure 9), a separate lamp is used in each unit rather than using one lamp for each optical axis; scaling circuits and the commutator circuits through which the

count is shifted to the spacecraft data storage and telemetry system are paralleled such that the frequency is counted by alternate scalars each one-half second (this also serves as a check against any malfunction in the counting circuit that would give an incorrect reading); separate power converters, whose supplies can be individually turned on and off by ground command, are used for magnetometer units A and B and scaling lines A and B; thermal controls for A and B units are similarly separate and supplied power from the corresponding magnetometer power source. As shown in Figure 9 the outputs of units A and B are mixed before entering the scaling circuits; this choice rather than treating the two outputs separately is made primarily to reduce the amount of data editing that would result from one of the two units frequently being in an orientation of low signal amplitude. The redundant features noted above have two primary consequences: (1) a failure in one of the magnetometer units will still permit data coverage of the type available from a unit with one optical axis when the faulty unit is turned off, and (2) a failure in one of the scalar-commutator units will reduce the number of measurements from 2 per second to one per second. There are, however, some types of single failures that can cause complete loss of data, both within the experiment and in the interface connections between the spacecraft and the experiment. Thus, the design is not completely redundant.

As indicated in Figure 9, temperatures in the lamp-sensor assembly, the duty cycle of heater controls, and signal amplitudes are also telemetered. These functions provide information that permits detection of a malfunction in either unit which may be correctable in some cases by turning power on and off by ground command.

Digital and analog outputs are stored for playback to ground stations and also read-out in real time by the spacecraft system when in line of sight of ground stations (Scull and Ludwig, 1962; Ludwig, 1963). In addition, the Larmor frequency, $f = 466744$ (F) , is divided by four, to fall within a 100 kc/s modulation limit, and fed directly to the Special

Purpose Telemetry transmitter where it is transmitted continuously along with four sub-carrier signals from other experiments. The primary purpose of this signal is to permit studies of field fluctuations at frequencies >1 cps over receiving station sites. It also serves as a check on the correctness of the digital system through all phases: experiment, spacecraft, and surface equipment.

The sphere enclosing the lamp-sensor assembly has a black surface over all areas exposed to the sun such that its radiation properties are predictable and not subject to change through surface contamination. Aluminum coatings are used on the surfaces of the lamp-sensor assembly to minimize radiation losses from the lamp and heater circuits. Active thermal control is achieved by having the passive, uncontrolled, temperature on the low side of the nominal 30° to 55°C operating range for the gas cells and then adding heat. Heat is added using bifilar, non-magnetic, circuits controlled by thermistor readings to several °C at the center of the temperature range. Heater windings are inside the cylinders shown in Figure 8. The winding that appears on the outer surface of the cylinders in Figure 8 is in series opposition to the Larmor frequency feedback coil and serves to keep the feedback field from one magnetometer from appearing in the other magnetometer.

Power required for the instrumentation, including conversion losses from the 28 ± 5 volt spacecraft supply, is 6 watts with an additional 2 watts required for thermal control. The weight of the lamp-sensor assembly is 2.5 pounds. The instrumentation within the spacecraft body, including power converters and containers, weighs less than 10 pounds.

5. WMS Data Reduction and Analysis

5.A. Handling of Raw Data

The POGO magnetic field survey is to yield two field measurements per second throughout the active life of the experiment and spacecraft instrumentation. This amounts to approximately 10^6 measurements per week, or 3×10^7 measurements in 6 months. The processing and transfer of this information from receiving station tape recordings to a computer tape suitable for analysis (See Figure 10) is a major undertaking. However, in terms of the complete POGO system this magnetic field information constitutes less than 4 percent of the telemetered experimental data and with the auxiliary information (See Figure 9 and previous section) on signal amplitude, heater cycles, and temperatures included, the total for the experiment is less than 6 percent. With the exception of the signal transmitted via the Special Purpose Telemetry the information is digital and the processing is largely a tape handling and computer operation problem. Signals received from Special Purpose Telemetry are processed in a system particularly designed for reducing data from optical pumping magnetometers. Unlike the spacecraft digital system whose measurements are set at twice per second with a precision of ± 2 cps in 466744 (F) cps by the technique of direct frequency counting, sample periods in this system can be set in 0.001 second increments from 0.001 seconds to 10 seconds and the technique of gating a 5 Mcs. reference frequency gives a theoretical precision of ± 1 part in 5×10^6 (Δt) where Δt is the set sample interval (e.g., ± 0.1 gammas in a 0.5 gauss field with $\Delta t = 0.1$ seconds). This provides a more than adequate check on the spacecraft digital system, but its principal use for POGO data is in studying rapid field fluctuations.

Inasmuch as analysis of the satellite data is dependent on knowing the temporal behavior of the field as recorded by surface magnetic observatories, the observatory records, which are generally in the form of 24 hour analog traces of D, H, and Z or X, Y, and Z, must
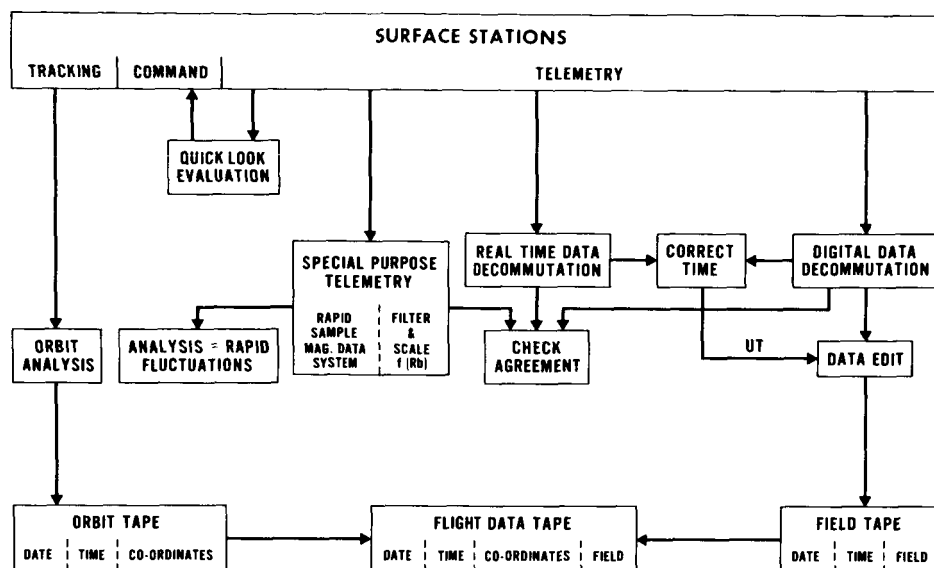
Figure 10—Reduction of POGO magnetic field data from telemetry tape

also be processed to place the data in a form suitable for analysis with computers (See Figure 11.A). The task of converting the analog records to digital form is not particularly formidable using modern equipment but the additional attention required in checking baselines, scale values, reproducing records, verifying scalings, etc. makes it desirable to use a selected set of observatories rather than all existing observatories. Factors such as the locations of observatories and the time-space scale of equatorial and high latitude magnetic phenomena do not, however, permit selection of an ideal minimum number of observatories. Preliminary planning suggests that approximately 50 existing observatories will provide a distribution that could not be greatly improved without establishing new observatories in the large regions of the globe that are currently not represented. Selecting a time interval between digital readings of observatory magnetograms presents additional questions for which there are not strict answers. The interval of 3 minutes, noted on Figure 11.A. has been tentatively selected on the basis that it is sufficiently short to reveal most of the level changes evident on magnetograms with recording speeds of 15 or 20 mm/hr.
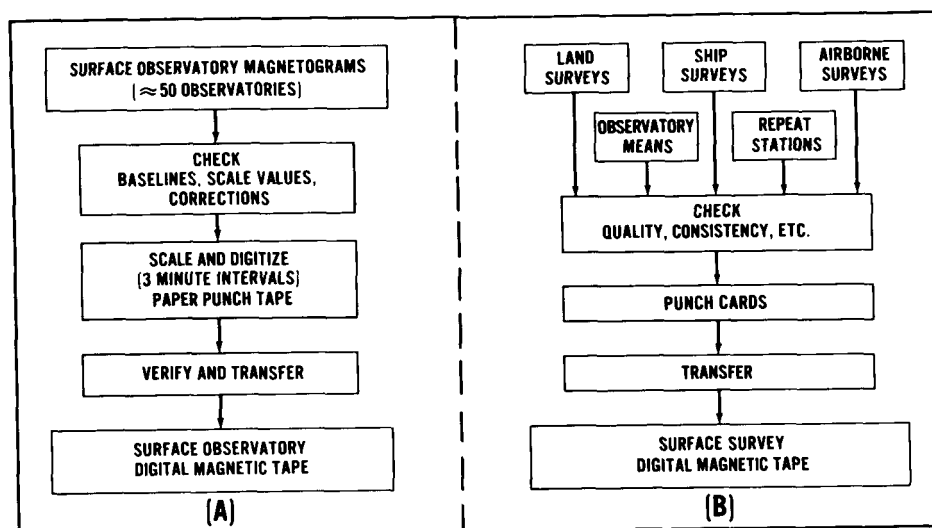
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Figure 11—Processing of surface magnetic field recordings and tabulated data

Utilization of surface survey data as an integral part of the analysis is also dependent on having the data in computer input form. As originally recorded most of the data from past and present surveys are in analog or tabulated form. In some cases the organization conducting the survey converts the recordings to a digital form such as punch cards. Efficient handling of the data from diverse sources is however dependent on having all the information in a common format. Within the United States a joint effort is being made by the Coast and Geodetic Survey and the Goddard Space Flight Center to compile all available survey data as illustrated in Figure 11.B. These organizations with the cooperation of the U. S. National Science Foundation are also planning the reduction of magnetograms illustrated in Figure 11.A.

5.B. Analysis Procedures

The direct application of techniques previously used in field fitting (See Section 3) to quantities of 10^6 to 10^8 measurements would

not be practical even by making simplifying assumptions such as neg-
lecting external sources and diurnal effects. When external terms are
included, as they must be to get a valid description, and/or coefficients
of $m = n > 6$ or 10 appear probable (See Section 3.C) the computation
effort assumes enormous proportions in terms of computer time per
coefficient. Solutions to this forthcoming problem are currently being
sought along two general lines: examining how the quantity of data can
be most effectively reduced with minimum loss of information, and ex-
amining alternative analysis techniques and the associated computation
problems.

There are of course obvious ways of reducing the quantity of
data such as merely disregarding all but a small fraction of the meas-
urements. This is hardly ideal, however, and the throwing away of data
points is best done, if necessary, after first applying a selection tech-
nique having some physical basis. Various techniques of simple aver-
aging or smoothing of data, such as applied to airborne data, are likely
to increase rather than decrease errors, as a consequence of the 4 km
separation of one-half second data points. One analytical approach that
would serve the same function as smoothing, but is potentially more
convenient in analysis, would be to represent the data along each orbit
by means of a Fourier series and then reconstruct a data grid for the
spherical analysis from the various Fourier series. In this and similar
techniques it is essential that the time of measurement be preserved in
the reduction technique such that diurnal and disturbance effects can be
analyzed and removed.

The most logical approach to reducing the quantity of data
for main field analysis is, in the authors opinion, one in which the data
is sub-divided such that: (1) measurements significantly effected by
magnetic disturbances do not appear in the main field analysis, and
(2) measurements are grouped according to local (solar) time such that
diurnal effects can be readily recognized. When measurements are
taken over periods exceeding several months a third grouping based on

the dates of measurement becomes desirable for recognizing secular changes. Sub-dividing the data in this manner has additional advantages in facilitating studies directed toward understanding the source and cause of the field variations.

The flow diagram in Figure 12 illustrates one method of approaching the data that fits the above criteria and makes use of the motion of the orbit plane with time to reveal diurnal effects. The diagram is self-explanatory but several steps require comment. The selection of "quiet periods" is based on surface observatory data as indicated in Figure 13. The selection, involving visual, range, and level criteria, is roughly analogous to using K_p indices along with a D_{st} (or D_0 as used here) analysis to avoid including storm recovery periods. A minimum quiet period (λ_i in Figure 12) of 24 consecutive hours is essential to obtain 360 degree longitude coverage in the two local time zones sampled each orbit. Long quiet periods (e.g., more than 2 days) improve the density with longitude near the equator, where density is needed, but also present a greater computation problem. At this point it will be desirable to make a second selection of the data (not shown) in which measurements taken at high latitudes during polar and auroral zone disturbances are thrown out. This is the logical place to reduce the quantity of data from both the standpoint of density per unit area and disturbance effects. If the number of measurements after these steps is still too great for computation efficiency, successive selections based on eliminating successively smaller disturbance effects can be applied. A very rough estimate of the number of suitable quiet periods that might be expected is 2 to 6 such periods each month having durations ranging from 1 to 5 days. Thus, when analyzed separately (Figure 12) it can be anticipated that a spherical harmonic description would be obtained for approximately each hour of local (solar) time after 6 months as a consequence of the orbit plane ($90°$ inclination) moving one degree per day in local time.
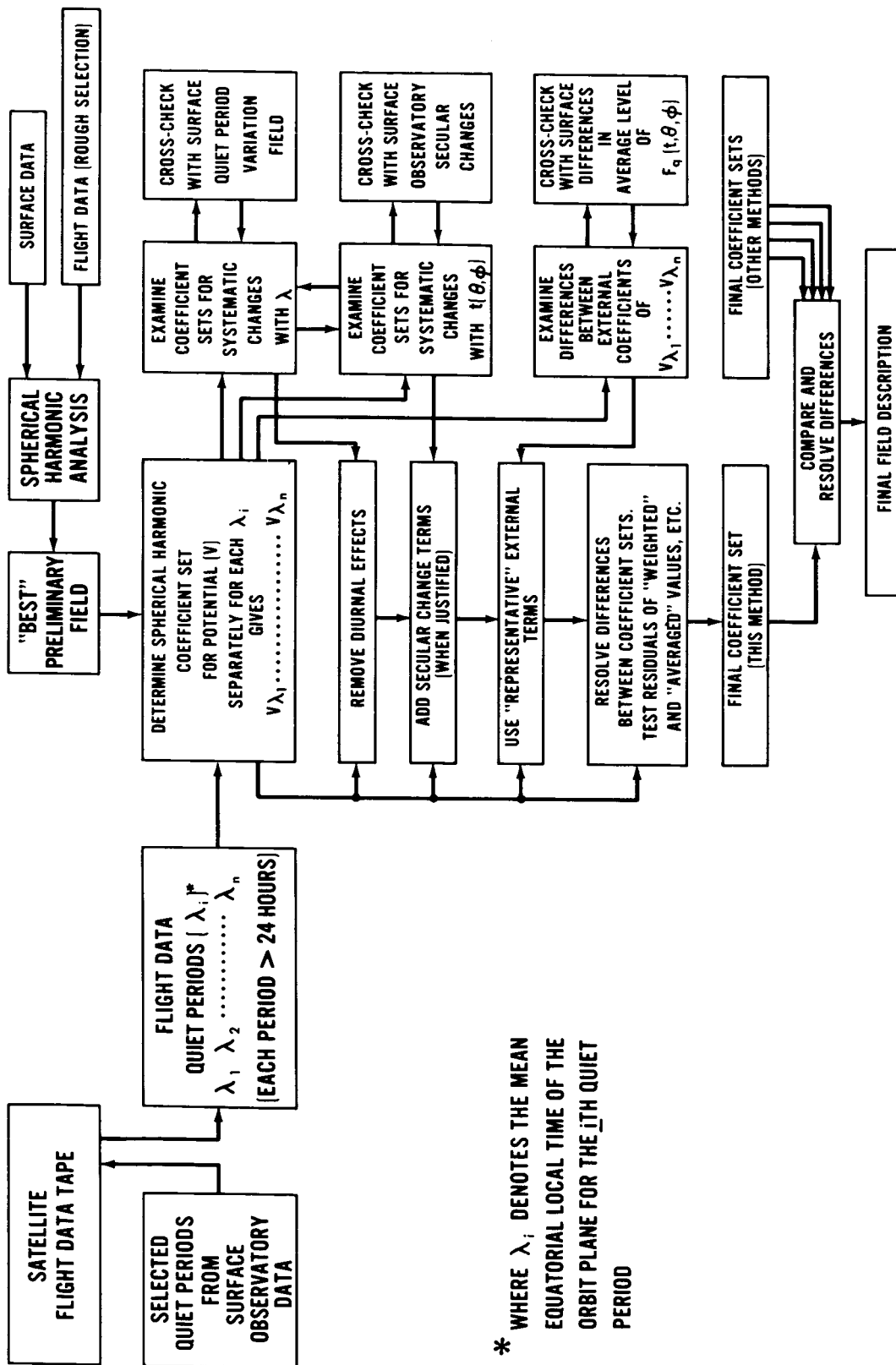
Figure 12-Functional diagram illustrating steps involved in one method of arriving at field coefficients not contaminated by diurnal, disturbance, and secular effects

The motion of the orbit plane with time, which makes λ_i equivalent to time, presents a dilemma in separating diurnal and secular effects. As the magnitude of secular change will over 6 months be equivalent to diurnal magnitudes in many regions of the earth, magnitude alone will not permit separation. Space will not permit full discussion here but it should be apparent that this separation will be dependent on analysis of secular change patterns at the earth's surface unless assumptions regarding the source of the diurnal variations are inserted in the analysis. Ideally one would prefer not to include such assumptions.

The difficulty and accuracy of resolving the differences between coefficient sets after removing the systematic changes depends on the magnitude of the non-systematic changes. In the case of external terms the observatory data on small level changes provides additional criteria. For the internal terms the differences may be extremely small in which case weighting and averaging according to some criteria such as mean residuals may be adequate. If the differences between sets are large the method has obviously failed.

Failure to achieve an accurate description is not likely if all the desired instrumental, spacecraft, and orbit criteria are met unless an invalid assumption is inherent in the method. The assumption of this type that is likely to cause the most trouble is the assumption that the region of measurement is free of field sources. Over the POGO altitude range, 250 to 925 km, this would appear to be a good assumption in terms of present knowledge but this knowledge is very incomplete, especially with regard to diamagnetic contributions at magnetic latitudes >45 degrees. If it is found that the assumption of no significant sources in the region of measurement during quiet periods is not valid, modifications in the analysis procedures will be necessary.

It has also been assumed that spherical harmonic analysis is the best method for achieving the field description. There are very few examples in past works involving the direct use of the equivalent multiple

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dipoles or surface integrals. McNish (1940) and Lowes and Runcorn (1951) have for example used graphical methods to locate a number of dipoles for fitting the main and secular change fields. Graphical methods are not applicable where large quantities of data are involved but the direct use of multiple dipoles is not necessarily out of the question. If efficient computation techniques for analytically adjusting the dipole locations and moments are devised there are possibly other computational advantages as noted by Jensen (1962). The total problem, including external sources, has however apparently not even been approached by these methods.

6. POGO Measurements of Temporal Variations

Magnetic variations of diurnal and disturbance character have been treated as undesirable noise in their relationship to the topic of this review. Their study is however an important part of the POGO experiment which should not go unmentioned. A review of the variety of field variations to be encountered in a low altitude orbit of 90 degree inclination is too large a subject to tackle here. A list of topics would include studies of: (a) the latitude-longitude distribution of the equatorial electrojet and related questions regarding the closure of the electrojet circuit and whether or not the non-equatorial S_q system is truly located in the E-region of the ionosphere, (b) the ionospheric or non-ionospheric source for the middle latitude field disturbances apparently associated with activity in the auroral zone and usually referred to as the SD and DS fields in harmonic representations (See Sugiura and Chapman, 1960), (c) the distribution of disturbance effects in auroral and polar cap regions, (d) the magnitude of diamagnetic effects associated with particle influx in auroral regions and questions regarding the existence of currents along field lines and the closure of auroral electrojet circuits, (e) the ionospheric attenuation and induction effects on hydromagnetic waves and transients as revealed by surface and satellite comparisons, etc. The analysis of surface observatory records
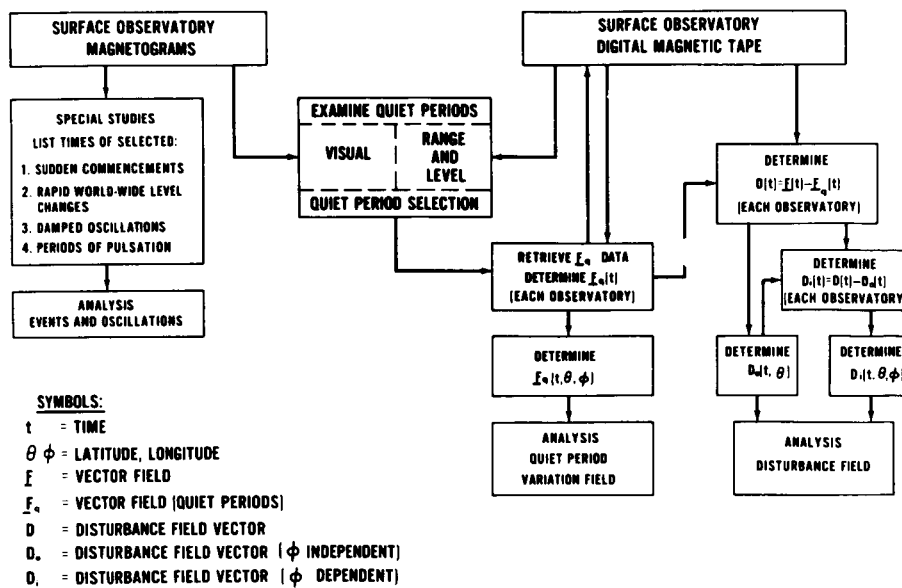
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Figure 13—Routine steps in analysis of surface observatory data

for comparison with the field deviations seen at the satellite is an essential part of these studies. Figure 13 outlines some of the routine steps in expediting the surface analysis.

The POGO measurements because they are scalar and not vector are not ideally suited for some of these problems. They will nevertheless give a vast amount of information on causes of magnetic disturbance that is not otherwise available — particularly with regard to localized effects and ionospheric currents which cannot be studied with higher altitude satellites (Section 8).

7. Secular Change and Future Surveys

The fact that the earth's magnetic field slowly changes in form and intensity has been recognized for several centuries and in very recent years there has been general acceptance of the belief that these changes have a hydromagnetic origin in the earth's fluid core (Elasser, 1950; Bullard and Gellman, 1955). The attempts of various

hydromagnetic theories to explain the surface patterns of secular change have given additional impetus to obtaining more accurate descriptions of these patterns. The principal impetus has come from requirements for updating magnetic charts in regions where recent measurements do not exist. For this purpose and for illustrating the patterns of change, charts showing contours of equal annual change (called isoporic charts) are constructed for each of the field elements (X, Y, and Z or D, H, and Z) and the total field (See Vestine, et al., 1947b for a description of procedures).

The sparsity of observatories and repeat stations makes the construction of isoporic charts highly subjective over large areas of the earth's surface. Thus isoporic charts, such as Figure 14, should not be expected to be correct in detail. Although there is reason for skepticism in using isoporic charts in many regions of the earth there has nevertheless been fair agreement in various analysis with regard to the major patterns and the movements of these patterns (especially the westward drift of the eccentric dipole) over the past 50 years (Vestine, et al., 1947b; Bullard, et al., 1951; Nagata and Syono, 1961; Benkova and Tyurmina, 1961).

Analyses are also consistent in finding that the dipole moment of the earth has in recent years been decreasing with time. The rates given by Nagata and Syono (1961) for 1955 to 1960 based on a spherical harmonic analysis of dX/dt, dY/dt, and dZ/dt are typical. These are: (a) the eccentric dipole moment is decreasing by 4.4×10^{22} emu/yr (total moment 8.05×10^{25} emu), (b) the eccentric dipole is drifting westwards by 0.3 degrees/yr, northward by 0.2 degrees/yr, and outwards by 3.4×10^{-4} earth radii/yr, and (c) other harmonics are drifting mostly westward and also at rates of several tenths of a degree per year.

Nagata and Syono (1961) and Nagata and Rikitake (1961) also point out that very intense foci appear in the isopors in the region of Antarctica with changes reaching 200 gammas/year in dZ/dt. Mansurov (1960) has also discussed the behavior in Antarctica, noted that change in the sign of dZ/dt at other locations as well is not rare, and states
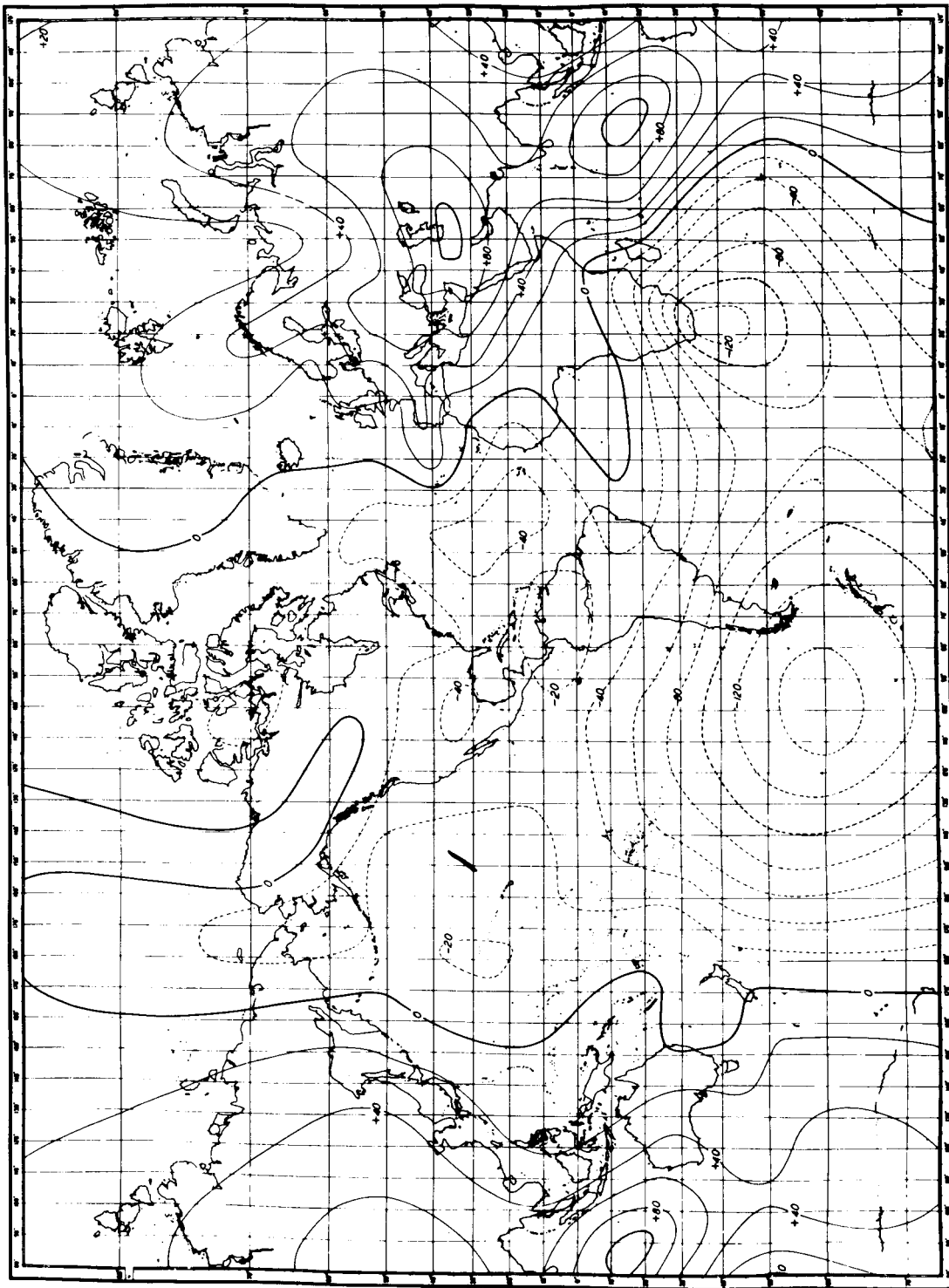
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Figure 14—Secular change of total magnetic field intensity in gammas per year, Epoch 1942.5 (Vestine, et al., 1947b)

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that superimposed periodicities of about two years were evident in Antarctica. The latter feature previously noted by Kalinin (1954) in other regions was attributed to the influence of external sources. Orlov (1961) has emphasized the need for examining solar activity effects in secular change studies.

From the magnitudes quoted above and inspection of isoporic charts such as Figure 14, it is apparent that the POGO satellite measurements over periods of 6 months to a year will be influenced by average values of secular change. In regions such as those south of S. America and S. Africa (Figure 14) and Antarctica the rates are such that they will not only be an influence but also should be detectable such that limited analyses can be performed. The prospects for determining the detailed world-wide patterns of secular change with follow-on satellites to POGO at intervals of 3 to 4 years are particularly good. In the regions previously mapped by Vanguard 3 in 1959 (Cain, et al., 1962a; Heppner, et al., 1961) there is the opportunity to study secular changes relevant to the first of the POGO satellites. These time scales for secular change studies are currently feasible only at observatories, whose distribution leaves much to be desired. The satellites should also demonstrate whether or not the present agreements in the characteristics of secular change have general validity or whether the agreements are primarily a consequence of different investigations using the same or similar data from the same observatory distribution.

8. Surveys of the Outer Magnetosphere

The WMS satellite (POGO) discussed is oriented toward obtaining the best description of the earth's main field at, and close to, the earth's surface. It should reveal the existence of external field contributions and the form of the vector summation within the volume swept out by the satellite. The description does not, however, give unique solutions for the locations of the external sources just as it does

not uniquely determine the locations of the internal sources. Thus one cannot necessarily expect to accurately trace the geometrical path of a field line extending to a number of earth radii even though its path up to some altitude (e.g., 1000 km if the POGO orbit is in a source free region) is well known in both hemispheres. Geomagnetic coordinates such as the L parameter for trapped particles, defined by McIlwain (1961), are similarly sensitive to external sources in weak field regions and determining the limitations will in the future rest on knowledge of the external sources.

A complete description of the earth's field in space requires direct vector measurements throughout the volume enclosed by the magnetosphere cavity formed by the solar wind. This is an immense region and any average or representative description would have to make allowance for large variations in $\Delta F/F$ with time. The existing vector measurements of Explorer 10 (Heppner, et al., 1963) and Explorers 12 and 14 (respectively, Cahill and Amazeen, 1963; Cahill, 1963) the two component measurements of Explorer 6 and Pioneer 5 (Smith, et al., 1960), and the scalar field measurements of the USSR Cosmic Rockets 1 and 2 (Dolginov and Pushkov, 1962) have provided important data for initiating this description.

Scheduled satellites which will provide considerably more data and additional coverage within, at, and outside the magnetospheric boundary include the series of Eccentric Orbit Geophysical Observatories (EOGO) and the Interplanetary Monitor Probes (IMP). The first two satellites in each of these series are instrumented with both rubidium vapor and fluxgate magnetometers. Initial flights in each of these series precede the POGO survey. This also means that there should be more definitive knowledge regarding external sources prior to the POGO survey. This information will further facilitate the analysis of external terms in the POGO field description — a fact which was purposely neglected in the preceding survey discussions on grounds that the survey data should be independently complete for main field description.

A very significant gap in achieving a description of fields in the distant magnetosphere is evident in the fact that current satellite schedules do not include magnetic field measurements at large distances (e.g. 0.5 to 20 earth radii) in high latitude regions. Field mapping in these regions is of utmost importance in terms of determining the entry into the magnetosphere of solar particles and the geometry of polar cap field lines that form the anti-solar "geomagnetic tail" in response to solar wind pressures. Hopefully this situation will be rectified in the near future to complete the outer magnetosphere survey.

9. WMS International Cooperation

The need for an internationally coordinated program in mapping the earth's magnetic field has been the basis for World Magnetic Survey planning (See Section 1). The recommendations put forth by international committees such as the IUGG-IAGA Committee on World Magnetic Survey and Magnetic Charts (Vestine, 1961) and the working groups for geomagnetism within COSPAR and the IQSY-CIG Committees are excellent guides for achieving coordination. They have in the past been lacking in one aspect which is particularly important to the satellite survey problem and that is the speed of transmittal of magnetograms and survey data to the World Data Centers, which were established during the IGY and are continuing operations for the WMS and IQSY periods. From the discussions in the previous sections it should be evident that surface magnetograms and survey data play an important role in the satellite data analysis. This analysis must also be conducted rapidly and efficiently and this becomes dependent on having the surface data available. In recognition of this factor the Working Group on Geomagnetism of the CIG-IQSY has recently recommended (2nd General Assembly, Rome, 1963) that observatories transmit copies of magnetograms to the World Data Centers for Geomagnetism within several weeks of the month of recording. This is a significant recommendation to groups feeling the

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responsibility of satellite surveys and the cooperation that will hopefully follow this recommendation will significantly contribute to the success of the WMS satellite effort.

10. Acknowledgements

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